RAMA RETOLD

By the Same Author

THE PREVALENCE OF [illegible]

THE STUMBLIN[illegible]

THE BACKWARD [illegible]

THE DUKE OF G

DEAD MAN IN T[illegible]

S[illegible]VER MA[illegible]

Rama Retold

AUBREY MENEN

AUBREY - MENEN

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I

An Old Story

THIS is the story of Rama, a prince of India, who lived his life according to the best advice. He reverenced his intellectual betters, who were called Brahmins, and did what they told him to do. He took his morals from the best moralists, and his politics from the most experienced politicians. As a result he was ruined, exiled, and disinherited: his wife was stolen from him and when he got her back he very nearly had to burn her alive from the highest of motives. In the teeth of the soundest and most reliable guidance from his moral and mental superiors, he finally recovered his country, his throne and his commonsense. He lived more than two thousand five hundred years ago but everybody will recognise his experiences.

Twenty-five centuries is a long time ago, but the Indians were in many ways as civilised as we are today. There were great cities with immense bazaars in which the shopkeeper cheated his customers and was in turn cheated by the merchants. The merchants were robbed by a vast civil service, and the civil servants kissed the big toes of the politicians, who were known as courtiers. The courtiers were Brahmins, and the Brahmins were the top dogs. They made the laws, taught the ignorant, dictated morals, controlled the temples and terrified the King. In those far-off days they had not yet become a rigid and hereditary caste. Any man could become a Brahmin provided he set himself up to know better than his fellow-men, and was sharp enough to get away with it. But a Brahmin was usually the son of a Brahmin, because the tricks of the trade took a long time to learn, and a man could not start too early.

Besides the Brahmins, there were men of genius. These were usually thought brainy but a danger to society and

they were customarily driven to live in the wilderness, another sign that this ancient civilisation was not much below our own. One such man of genius, was Valmiki who wrote the story that I am going to re-tell.

It is said that the tale of Rama's adventures is the first story ever put together. I do not know that this is true: but it is certain that Valmiki was the first human being to be recognised as a literary genius. He was therefore penniless and much disliked. He lived in a thatched hut and had to grow his own food. He could move among his fellow-men only if he were heavily disguised, and then at the risk of his life. He was an outlaw.

The Brahmins said (and their views have survived down to our own times) that he was a brigand in his youth, and in his maturity he became an assassin. This may mean that when he was young he stole other people's property and, when he was older, killed someone. On the other hand it may mean that his verses scanned better than anything the Brahmins could write themselves. We have no sure means of knowing which interpretation is the true one, but it should be noted that some of Valmiki's poetry is extremely good.

The Brahmins said that the man he killed was one of their fraternity. The killing of a Brahmin was the most heinous crime that the Brahmins could think of: but subsequently, millions of Indians who are not Brahmins have not taken too gloomy a view of it. His crime, if he did commit a crime, has not diminished his fame and has added, for some, to his personal charm. He has obstinately remained the greatest of Indian authors. Unfortunately, generations of Brahmins have re-written his poem so that in parts it says the opposite of what Valmiki plainly intended. While restoring his tale I shall not attempt to revive his language: I shall aim at reviving his attitude of mind.

This will mean rejecting whole sections of the work that the Brahmins have written into it, and inventing much that they destroyed: a drastic course, but then I am not, myself, a Brahmin.

II

The Old Story, made New, Begins

THE traveller to Ayoda, having crossed a pass between flat-topped hills and descended to the plains, came first upon a road lined with tombs. These were rounded structures, like the top half of an egg, with carved bands telling stories of the gods. They were surrounded by a thick railing, sometimes of wood, sometimes of stone, but always rich with sculpture. Under the egg was a small chamber and in this, resting on a shelf, an urn holding the dead man's ashes. This avenue might well have been a gloomy approach had there been any sign of mourning on the tombs. There was, however, none. They gave, as they were intended to give, the impression that the dead man had been comfortable and respected here on earth and was confident of being treated in the same manner beyond.

The gate of the city lay at the end of this avenue. It was a low affair with two towers. It had heavy teak doors, folded back during the day, and closed during the night. A few minutes before it closed a great thumping and roaring would break out from a small chamber immediately above the arch. This was the ceremonial drum, an affair of ox-hide some eight feet across and beaten by four men with heavy drum-sticks. On the nearby battlements other men would blow into the pointed end of large conch shells, that made a mournful sound, half-animal in quality, but of a power to carry across the whole city, a matter, perhaps, of a mile.

The road underneath the gateway was the only paved road in Ayoda, which it bisected. It was marked on either side by two deep grooves made by carts and chariots. Once a cart entered the gateway and its wheels fell into those grooves it was compelled to follow them. There was no way of getting out of the ruts made by its predecessors. The

inhabitants made no objection to this because it was the principle on which they ran their own lives.

The single street was lined with the houses of the rich: behind them in a tangle of mud alleys were the huts of the poor. The houses of the rich had plain walls facing the street with a stone symbol to indicate the owner placed near a tall doorway. When the doors stood open the traveller could see into a courtyard, open to the sky and surrounded by a colonnade. In the middle of this courtyard stood a stone altar. Here the head of the house made his sacrifices to the gods. Since respectability required that he do this at least six times a day, the traveller would stand an excellent chance of seeing him at his devotions.

He would usually be a man of good stature, pale brown or even ivory in the colour of his skin, a great deal of which would be visible since his only garment during these religious moments was a loin-cloth of fine material reaching below the knees. He would be surrounded by his family, the women swathed in coloured saris, which they held together over their faces and looked through a fold.

Other sacrifices would be constantly in progress at the main temple of the town, a large structure which lay in a piazza midway along the street. It was a pyramid of stone, all carved, and entered by a doorway writhing with allegorical figures. The piazza in front of it would be filled with people at most hours of the day and during the first part of the night. One type of person was immediately distinguishable from the rest. These people were much darker in complexion than the others and appeared to avoid any direct contact with their paler co-citizens. These black men were princes, sons of the blood royal, dukes, landowners and knights. They owned the land on which Ayoda stood, but they had had the misfortune of having it taken away from them by armed robbers in the past, the robbers being the ancestors of the more fair, and Aryan, inhabitants. The early Aryans, since they knew that the black men were the true owners of the soil, were forced by the nature of the case to

decree that the black men were particularly disliked by God, who specifically wished them to lead unattractive lives. The Aryans, thus fortified, gave the black men, among other similar duties, the sole right to clean out the city's latrines. This made the black men as important in the life of society as they had been when they were landowners, but they were less well rewarded.

The next class above these were the merchants whose shops and warehouses made busy the long stretch of the road that led from the main square to the gates of the palace. In the palace lived the King (who was a noble descendant of the original conquerors) and his government, which was made up of Brahmins who were the highest caste of all. At the time of this story the King was called Dasa-ratha.

King Dasa-ratha, Rama's father, was loved by all his subjects and he loved certain of them in return, especially if they were women. His one wish for his people was that they should, every one of them, enjoy all the good things of life, and he sincerely hoped that they would find some way of doing it. Meantime, he set them an example by enjoying the good things of life himself.

One of these good things was his vast palace, in which the King pursued happiness with the same ardour as some men pursue moral perfection, making himself equally miserable in the process. The palace occupied a quarter of the whole area of the city, of which only a fraction was devoted to the King's debaucheries. The rest was composed of great courtyards, surrounded by porticoes and columns, each courtyard having at one end a large hall, the roofs of which were held up by pillars carved in the shape of a lotus, or a rearing horse, or four elephant heads or warriors back to back. These halls were named according to their intended function.

The most splendid of these courts was the Hall of Audiences. Here the King received his subjects. The humblest inhabitant had the right of access to his monarch, provided, out of respect for his King, he covered himself with the official robe of audience, which was edged with

gold braid and could be purchased from the Master of the Robes at a price fitting to the dignity of the occasion. The fortunate person then approached his lord by edging himself forward with his elbows, flat on his belly.

One of the reasons for King Dasa-ratha's immense popularity with all classes was that, while holding audience one day early in his reign, he observed that some of the more elderly of his subjects were caused pain by the unevenness of the floor in front of his footstool. He had immediately given orders that it be re-laid with the smoothest marble.

A leather merchant who remarked in public that it would have been simpler for the King to have ordered that his subjects approach him on two feet, like men, instead of on their bellies like snakes was given the mild punishment of being beaten with one of his own straps in front of his jeering neighbours.

He had not received more than five hundred strokes before he admitted in a loud voice, that crawling on one's belly was a highly suitable posture for a citizen when faced with the power of the State in person, upon which (by a kindly forethought of the King himself) he was released.

The next most splendid hall was the Hall of Justice. The system of justice in Ayoda was the wonder of the Indian world. Every man was equal before the law. If a dispute arose between a rich man and a poor one, and if the latter were too poor to hire a lawyer, the Court would appoint him one from out of the waiting Brahmins (all lawyers were members of this distinguished caste) who was not allowed to accept money, and who must forthwith plead his penniless client's cause. This he would do to the utmost of his ability; much depended for him on the way he conducted the case. Many of the most wealthy advocates had won their spurs in such poor man's cases, since it was not easy to plead a case at an instant's notice and make a showing against a lawyer who had been studying his richer client's case perhaps for months.

Not only was every man thus given an equal chance

before the judges, the judges themselves were impartial. They were always appointed from amongst the most successful and experienced pleaders, it being an established principle that the man most likely to arrive at the truth in a legal matter was the man who had spent the greater part of his life doing his best to conceal it. However strange this rule may appear at first sight, it should be noted that no better has yet been discovered.

Nor is this surprising for the major discoveries in the method of governing mankind had been hit upon very early, for without them men could not be governed at all. Thus the next hall was called the Hall of the Exchequer, and although the accounts were kept in a primitive manner by notching sticks and flicking the beads of an abacus, the method underlying the collection and the assessment of taxes was as sound as any used since and in principle much the same. The Controller of the Exchequer taxed the people as much as he thought they would bear without violent protest: and when he was wrong the King declared a necessary war. These wars were called necessary both because they were useful in defending the frontiers and because they made it possible to levy double taxes. Occasionally the King did not have to declare a necessary war. A neighbouring kingdom did it for him. When the armies of the enemy approached the frontiers it was usually found that the Royal Armoury (a part of the palace that we shall not trouble to describe) had far too few bows for the archers, and a perplexing deficiency of arrows; the pikes were rusty and half of the spears were stolen; and not one quarter of the chariots of war would be found fit to take the road. Only the elephants would be found to be in fighting condition since these were taken out twice a year in public on the occasion of religious processions. Neither the King nor his Controller troubled to excuse these deficiencies. But when the public dismay was at its height, they would execute a General. This always restored public confidence, though how, and in what, it would be difficult to say.

Behind the Exchequer were the women's quarters, and here, owing to the proclivities of the King, was the real centre of government.

If the morals of the Exchequer are familiar, the morals of the Bedchamber are not. By law and by divine sanction the King was allowed as many wives as he could keep: that is to say, as many as the public would pay for, and the public was very indulgent.

This was because the priests explained that the custom made sure of the succession to the throne, and the unthinking members of the public accepted this explanation as satisfactory. The citizens who looked more deeply into the matter saw clearly enough that it did nothing of the sort: since the King produced a great number of sons, the succession was very much a lottery, and often a bloody one. But even those thoughtful people approved of a plurality of queens, because it gave the King something to divert his mind from ruling his subjects: and if subjects are ever to live a quiet life, this is an essential facet of political organisation.

The King, like all men of wealth and leisure, also kept concubines, and King Dasa-ratha kept them in profusion. But here again the system of having more than one official wife had its advantages, for the wives kept the concubines in their place, which nobody else could do. It is notoriously beyond the capacity of one single wife, acting alone and in embarrassing circumstances. But several wives shared both the shame and the vigilance, and succeeded.

To judge from the bustling life of the overcrowded harem, Dasa-ratha might be thought to have been an attractive and passionate man. He was, in fact, neither. He was a round man with short legs and short arms, with a forehead, nose and chin that together followed the curving contours of half a melon. As for his passion, he was frequently in bed, but finicky, and in seeking to prove himself a stalwart male, showed himself to be something of an old

woman. He planned his debauches beforehand in great detail and if ecstacy is to be achieved, like genius, by taking pains, his life would have been blissful though possibly short. The atmosphere he produced, however, was less that of romance than of a pernickety review of a regiment consisting of one imperfectly trained recruit. But he thought himself a great voluptuary, and that was a matter in which his own opinion was the only one that counted.

His eldest son Rama was in his twenty-fourth year when he gave the King a parrot. He did this because he was warm-hearted, generous, and a loving son.

But he was many other things which it is not wise to be at Court. He was handsome and the King was not; he was fonder of the hunt than the women's quarters, while the King hunted for the same reason as he ate gold leaf, namely because his anxious physicians told him it was an aphrodisiac. Rama's conversation was sober and manly; the King was a gossip. Rama's wife, Sita, was devoted to him; the King was devoted to his wives, a very different thing.

Rama was therefore by no means the King's favourite son but the King was touched when he gave him the parrot. He had a cage of silver wire made and had it set with semi-precious stones. He would point it out to his courtiers saying: "That is the first thing I have been given for twenty years without the giver expecting anything in return." The third time that he said this, the Lord Chamberlain thought of a reply.

"Majesty, what should he expect from you?" he said. "When you die everything you have will be his. God grant that he has to wait a hundred years."

From that moment the King was satisfied that Rama plotted his death. The Lord Chamberlain was granted the revenues of three temples for his vigilance in warning the King of a conspiracy which he had invented in a moment of spleen. From the moment of his being rewarded with the revenues of the temples, he ceased to be a courtier and

became a statesman. That is to say, he invented, and suppressed three more conspiracies in the next two years and was regarded as the saviour of the State.

One day Rama's parrot bit the King's finger.

Dasa-ratha conceived the idea that the parrot's beak had been poisoned. He consulted his Lord Chamberlain who answered that it was quite possible to poison the beak of a bird and that three hundred years ago a certain King of the Western Marches had been assassinated (it was said) by this very means. The King's suspicions were thus confirmed and he ordered his personal servant to wring the bird's neck and leave the body on Rama's couch.

But the servant despised the King, and being privy to all his excesses, was sure that he would soon die. He had no wish, therefore, to embroil himself with the King's successor. He lied to the King, told him that the bird was dead and placed on Rama's couch, but in fact he had given it away to a young woman of the court. The parrot bit the young woman of the court, who in turn gave it to a concubine, who kept it, for she was the one person that the bird did not bite.

III

The Ups and Downs of a Concubine

THE concubine almost immediately fell out of favour with the King (for talking after the lights were out, a thing he could not abide) and she was relegated, both she and her parrot, to the back-quarters. Her maiden beauty ripened with the years at much the same pace as the King's taste. Three years after her fall she caught the King's eye as he was touring the palace with his master-mason and she was restored to favour. A sentimental woman, she wished to leave the King a memento of her second honeymoon with him, and she gave him the parrot.

Her second fall was dizzier and deeper than her first. The King recognised the parrot and its cage, and the concubine was thrown into prison. At his next meal the King summoned Rama, and when the dishes had been taken away, he sent for the parrot and had its cage placed in front of the low stool on which Rama sat.

He then asked Rama to give it a piece of sweetmeat. Rama obeyed. The bird snatched the food, but did not bite the King's son. This ruse having failed, the King sought another, for he was now obsessed with the need of testing whether the parrot's beak was envenomed or not. The Lord Chamberlain, reading his mind, cast his thoughts round the palace for a person who was sufficiently obscure for the test. His powerful mind had already seen that the stability of his personal government and hence the future of the State depended on his seeing to it that the test succeeded.

"The bird, Majesty," said the Lord Chamberlain, "reminds me of an old nurse who looked after your second wife's son, the Prince Barat. What was her name?" he went on, meditatively. "Ma, Me, Mi, Man, Mun."

"Mantara!" said the King, with delight, immediately seeing the resemblance.

"Your Majesty's memory is astonishing," said the Lord Chamberlain, without flattery, for the Lord Chamberlain never ceased to marvel at the way the King's mind retained the smallest detail connected with the women's quarters, while unable to hold anything else. The Lord Chamberlain thanked the gods for the King's memory daily since it enabled him to govern the Kingdom without interference. "Why not send the bird to her?"

"Send the bird to her?" said the King. "Why? Oh yes. Yes. I see. A splendid idea. A splendid idea. Send it to the nurse Mantara with my compliments and say it will save her the need for a mirror."

The courtiers who were dining with the King chuckled at the royal jest. The courtiers who were standing behind the dining courtiers laughed loudly to draw attention to themselves; the courtiers who were watching the scene of the banquet from the end of the room roared with mirth till they cried although they had not heard the joke; and the courtiers who had not been invited into the banquet hall at all but were listening under the windows slapped their thighs, wiped their eyes, choked and gasped for breath, asking one another if they had ever known the King to be in such a jolly mood.

The bird was taken away by the Lord Chamberlain, its beak instantly anointed with poison, and it was despatched to Mantara. The King's physician was warned to be in readiness, the Chamberlain's assistants were told not to leave the palace, and the Chamberlain's supporters among the rest of the Brahmins were warned that something was brewing. The Chamberlain permitted himself a small brass jar of fermented palm-tree juice, and relaxed until it was time to save the nation.

This Mantara was an ugly woman of some fifty years. Since Dasa-ratha in his search for delight produced a great number

of children, the women's quarters swarmed with nurses. They were important to their charges while the children were still young, but to nobody else. They were engaged by the High Steward, who selected them rigidly according to the size of the bribe that he was offered. When Dasa-ratha's second wife produced a boy called Barat, this nurse was appointed to look after him. This she did well enough, but not in a way to attract any attention.

Bàrat grew up, and Mantara grew ugly. She was pensioned off with a room and something to eat daily from the scraps of the royal banquet. Her room was one of the very few that were higher than the single storey of the main palace, and was in fact, no more than the hollow inside of a carved, pyramidical turret that had been added as an architectural fancy. Mantara was so forgotten that no-one in the Palace knew for certain where she lived, except the kitchen-hand who brought her food.

One day, with her food, the man brought her a bird in a cage. The bird was a very old parrot with tattered plumage and a bad temper. It rattled savagely at the bars of its cage with a scarred and peeling beak as the servitor, planting the cage down beside the dish of food, told Mantara the astonishing news that the bird was a present from the King.

"The King himself?" asked Mantara, getting up from where she was squatting on the floor.

"Yes," said the serving man. "They say he's drunk now but I don't think he was drunk when he sent this. I kep' it by me while I did the sweetmeats. Nobody else could bring it 'cause nobody knew who you were."

"Except the King," said the ugly woman sharply. "Except the King: was there any message?"

"Not that I know of."

"There must have been a message!"

"There wasn't."

The nurse stamped her foot and screamed.

"You've forgotten it, you idle fool. Go and find out what it is! Go at once, you greasy good-for-nothing."

Saying this she aimed a box at his ears which he only avoided in part.

He turned on his heel and stamping down the narrow stairs that led to the turret he swore loudly by the more obscene of the popular gods that he would never set foot in the nurse's room again.

The poison was excellent. It would have killed Mantara with terrible agony within an hour, had the parrot bitten her. It killed, however, the bird instead. When this news was brought to the Lord Chamberlain he hesitated for a while between dismissing the whole matter, or announcing with suitable alarums that a parrot which had been given the King had been found dead with poison on its beak. There were two things against the latter course. The first was that everybody would suspect that he had put the poison on the bird's beak: whereas with a dead old woman being carried out of her room feet first and horribly swollen, nobody would have thought him capable of such a monstrosity; secondly, it was the plain truth, even if not all of it, and although he was prepared to admit that telling the truth was not always harmful, he had never, in twenty years of politics, seen much good come of it.

So he did nothing. He told the King that there was no evidence of a conspiracy at the moment, and to the people he issued a proclamation declaring a public holiday in celebration of the King's continued safety. He had made an irretrievable blunder. He annoyed the King; while the people were convinced that he was fobbing them off. The adherents to his party whom he had warned that something was about to happen began to talk openly of his losing his grip. When he contracted a cold in the nose, it was rumoured that he suffered from a malignant disease in a disgraceful part. The Lord Chamberlain was too good a politician either to miss these signs or to discount them.

He cast about to find means of preserving his reputation for being the man the country turned to in a crisis, but the

stars in their courses fought against him. There was a bumper crop, there were no disastrous droughts, nobody (it seemed to him) had either the brains or the courage even to think of sedition: and to crown matters, the rainy season was approaching and he could not start a war.

In this last matter, however, he did his best. He sent an insulting embassy to a touchy neighbour state, but it did him no good whatever. The Lord Chamberlain of the insulted State, himself a Brahmin and a statesman, privately asked the ambassadors if their master did not know that elephants, when in mud, invariably got stuck and that this brought derision on even the most Necessary War. When this remark was hesitatingly conveyed to him by his abashed envoys, he began to consider whether for the sake of his place in history, he would not have to poison the King himself.

Thus oppressed by contrary events, he decided to question the concubine. In a cooler moment he would have seen that this course might well lead to further embarrassments, and since the concubine could not possibly know anything, he would not have had her tortured in order to think of lies which he could better concoct himself. He was not a cruel man. He was, however, in a hurry.

The concubine was therefore taken to another room in the jail and jerked up and down on a rope which hung from the ceiling. The rope was fastened to her wrists and these in turn were disposed behind her back, in a position best calculated to stimulate her thoughts on constitutional problems. She was spitting blood before she was told what her torturers were aiming to find out. They then let her down and giving her a drink of water, asked her:

"Did you conspire to kill the King?"

She should, according to previous experiences, have muttered incomprehensibly in answer to this, from which mutterings, with the renewed aid of the rope, a connected answer could have been built up.

But the concubine was neither a frightened chit of a girl

nor a weak old woman. She was in the prime of a none too easy life. Twice she had emerged from obscurity into the light and warmth of success, both occasions being those in which she had received the favours of the King. She clung to these triumphs with the determination of a woman who knows she cannot have many more such in front of her. She massaged her arms, brushed her hair from out of her eyes and asked that the question be repeated.

They said:

"Did you conspire to kill the King?"

She answered, in unblushing vernacular:

"I slept with His Majesty six days ago. I don't know anything about killing the King. All I know is that I thought he would kill me."

The answer was all round the Palace in an hour. The Brahmins who had the hereditary honour of waiting outside the King's privy shouted it through the door. The King was delighted. He denied having heard the remark twenty times in the course of the morning in order to have the pleasure of hearing this simple but impressive evidence of his prowess repeated again and again. Shortly before going into his midday meal he swore that he would give the concubine the privileges and apartments due to a royal wife. By the time he had finished eating, the forthright woman had been washed, scented, given a cordial and handsomely robed, and her two torturers had kissed her toenails and begged to be recommended to the King for their devotion to duty.

The Lord Chamberlain met the King for the first time that day as the King retired for his siesta. He read his fate in the King's eyes. By the time that the King and the royal guard were well set in their afternoon sleep, the Lord Chamberlain was on his way to the frontier. By night-time he was across it and in a matter of hours was being received with every mark of distinction by the other Lord Chamberlain who had been so disturbed by his apparent lack of knowledge of warfare and elephants. He told his story to

sympathetic ears since he had brought a camel loaded with a portion of the year's recently collected taxes.

In a short time he was presented to a courteous monarch and a wildly cheering populace as the man, who, at the risk of his life and the cost of his career, had dissuaded the King of Ayoda from following up his notorious ultimatum by bloody and aggressive war. Henceforth he was popularly known as the Peacemaker and plays no further part in our story.

The concubine accepted her honours with grace and dignity. She recommended the torturers to the King, and thereby made friends of the two best-informed men in the palace. This rendered her position impregnable, and she died, years later, much respected.

IV

A Procession is Postponed

THE dead parrot, merely as a decomposing bird, was fit to feed a few maggots and enrich a few inches of soil. By the alchemy of human folly it was enabled to ruin a career, change the government of the country, and elevate an old woman to fortune and power. The old woman was the nurse Mantara. She achieved her position not because she was clever, industrious, talented or gifted but because she was half mad. The recipes for worldly success are greatly varied.

Mantara had the dead bird stuffed. She put it back in its silver cage and waited. She waited with great confidence, even though she was driven to fetch her own food, the servitor refusing to wait upon her any more. Then she was utterly alone but she was sure it would not be for long. She was convinced that the King had sent her the parrot as a sign of some special favour that was to come her way.

Nothing at all happened. She dusted the bird, and raised her hopes.

Now it was customary for the Kings of Ayoda to hold a festival on their fiftieth birthday, should they attain it, in which they proceeded in state down the principal road of the city, seated in an elephant howdah with their eldest son beside them. The Kings were traditionally required to make this journey leaning their right hands symbolically on their son's shoulder. This served to declare that the succession was secure. It was also the tradition that on this day, and for some days previously, every building in the city should be decorated with flags. Some months after the flight of the Lord Chamberlain the King achieved his fiftieth year, the loyal populace hung out its flags, but the King swore that

he would see the royal elephant trample Rama to death before he would ride by his son's side and declare him heir.

The Brahmins closest to the King shook their heads. The tradition was a deep one, they said. If the King broke it, the people would take it as a sign that good luck would desert them and the crops would fail. The King replied that this was superstition, at which one Brahmin arose and said that he agreed with the King and that the best way to fight superstition was by scientific thinking. Most of the younger Brahmins and, of course, the King, greeted this argument with approval. The Brahmin then went on to suggest to his Majesty that the royal astrologer be asked to make the most stringent observations of the stars to see if, by chance, it should be written there that the procession should be abandoned owing to the unfavourable conjunction of (for example) Venus and Saturn. The King was pleased, the other Brahmins were impressed, and the man with the idea was elevated to the vacant post of Lord Chamberlain.

The Royal Observatory was a wide platform at the top of a flight of steps from each of which calculated observations could be taken with the cross-staff. At the top, on the platform, were stone quadrants with spy-holes in which stars appeared at certain fixed times. With the aid of these the Royal Astrologer had been able to predict eclipses of the sun for the next fifty years. These and other predictions were considered as being of vital importance to the State, especially in time of war, when a true knowledge of the movement of the heavens was a great advantage over the enemy. The royal astrologer enjoyed the protection of the King. He had full freedom to pursue his researches: but since they were so important it was decreed, as a precaution, that if he should tell them to any person other than the King or his appointed minister, or even if there were grounds to suspect him of telling, then he should have his tongue torn out by the roots. While the royal astrologer could predict what would happen to the sun in the next half-century, he was quite unable to predict, therefore, what would happen

to himself in the next half-hour. He was an obliging, but apprehensive man.

Nervously mounting the steps of the Royal Observatory that night to make the crucial observation required by the King, he saw that he was being followed by two men. He turned to ask who they were, and they said that they had been sent by the King to help the astrologer make his observations. They also said that the King hoped very much that the stars would be found to advise against a procession, but that he did not want to interfere with the learned man's methods. The astrologer bowed, the two men bowed, and then threw back their hoods. By the light of the lamp which he carried, the astrologer could see that they were the King's torturers.

"Shall we go on up?" said one of the torturers.

"Gentlemen," said the astrologer, "I think we can all save our breath. We may dispense with the climb. The stars, like everybody else, are only too anxious to please His Majesty."

"Our orders," said the other torturer, "were to help you. His Majesty was very pertickler that you should do all the squinting that you wanted. No violence, no interference, was his very words. We was to 'elp."

"Gentleman," said the astrologer again, trembling from head to foot, "I know my job and I am well aware that you know yours. If I start my squinting, as you so accurately call it, I shall only confuse myself. The stars, I feel tolerably certain are very adverse to the holding of a procession, since the relevant planets were in a most unfavourable conjunction the last time I observed them."

"You hear that?" said the first torturer to the second.

"I do," said the second.

"You know what he means!" asked the first.

"I don't," said the second.

"My friend don't know what you mean," said the first torturer. "Would you tell him?" he asked the astrologer, politely.

"I mean the procession's off," said the astrologer, his teeth chattering.

"There you are," said the first torturer. "It's all settled."

"I shall," said the astrologer, gathering a little courage to uphold his professional dignity, "have to make a few calculations and checks. I can give the King a positive answer tomorrow or the next . . ."

"Our orders . . ." began the second torturer, but his companion interrupted him.

"Look at it this way," he said, "if we had this learned gentleman here tied up with weights on his feet, and you did you know what, and I turned the little so-and-so, and he said 'The procession's off,' would we let him down?"

He had accompanied the supposed prisoner's words with a scream of agony that was most realistic. It echoed round the stone observatory and inside the astrologer's head.

"Well," said the second, "yes, we would."

"Then there you are," said the first. "We've done our duty."

"Yes," said the second, "but we haven't tied him up yet."

"And *I* say," said the first, "that's all to the good. We don't like hurting people. We take a pride in it, yes. But we don't *like* doing it. It's just that we are ready to serve our country, same as soldiers. Do you see?"

"Yes," said the other. "I always do when you explain things. I sometimes wonder why you don't go in for politics."

"I do," said the first, and both laughed so heartily at this jest that the astrologer had to sit down on one of the observation steps, his knees having turned to water.

When he recovered his breath he explained that he had just done all the necessary calculations in his head.

"What a brain!" said the second torturer, admiringly.

"What talent!" said the first. "His Majesty would like to hear of this straight away I'll be bound. He's waiting for the verdict in the Royal Wardrobe."

Next morning the great State drums in the chamber over the gateway roared a summons to the people. A few minutes later the iron-studded doors were hauled open and a cavalcade ablaze with the royal colours of orange and white came out, their horses prancing, and rode at a dashing pace to the central square.

They took up a position in line facing the crowd with their backs to the carved stone pyramid of the principal temple and a young man in a sash of gold embroidered with rubies and moonstones held up his hand. The horsemen at the two ends of the line swung the mouthpieces of their trumpets to their lips and blew. The stems of the trumpets curved round their bodies and rose over their heads. From their bronze mouths embossed with hemispheres, one lacquered orange and the next white, came an inspiriting roar of sound.

The young man said loudly:

"In the name of the King!"

The trumpeters blew another blast and all the horsemen lifted their lances from which hung oblong pennants of the holy colour of saffron.

The men in the crowd bowed their heads and touched their foreheads. The women drew their saris more closely over their faces, and peered through the folds at the young man.

The principal horseman moved his horse with infinite grace of carriage until he stood in front of the others. He then made his proclamation, saying it first in the stilted Sanskrit that only the Brahmins used and only the Brahmins could properly understand, following this by an explanation in the vernacular which he delivered with great vigour. He showed the whites of his eyes as he rolled his glance over the crowd and he was greatly admired by everybody.

He announced that owing to the findings of the great astrologer (and here followed a long reminder of the great astrologer's previous scientific triumphs including the prediction of eclipses) the King would have to forego the

pleasure and honour of receiving the felicitations of his loyal subjects on the occasion of his fiftieth birthday, and also to forego the privilege of presenting them with their future ruler (and here the expected name of Rama was omitted). The King, said the proclamation, had been warned by the astrologer that the direst consequences to his beloved people might follow were he to flout the message of the heavens. Since the well-being of his subjects, whom he looked upon as a father looks upon his children, was always first in the King's mind and always nearest his heart, there would be no procession. They could take down the decorations.

The horseman backed his horse with consummate skill into the rank behind him, the trumpets bellowed again, and then broke into the Royal Anthem, a simple melody (the trumpets had only seven notes) but very stirring. With pennants waving and many dashing looks to the left and right, which the women in the crowd received as especial tributes to their figures, the cavalcade rode back to the palace; the drums over the main gate throbbed again, the horsemen clattered inside, and the gates were closed.

In the main square in front of the principal temple comment was divided. There were those who had been moved by the handsome display and who had felt a constriction of the throat when they heard the anthem. These said that it was a bitter shame but that it was typical of King Dasaratha to put the good of his subjects before his own pleasure and that it was a wonderful thing to be a citizen of Ayoda. Where else, they asked one another, could a man of learning go straight up to a King, bold as brass, and tell him to his royal face that he could not have a birthday procession. In the Kingdom of Vamsa he would have been boiled in a cauldron of oil, in the Kingdom of Magada he would have been sewn up into the raw skin of a wild beast and put in the sun till he was squeezed to death; in the Kingdom of Avanti he would have been sent to labour in the rock-salt mines. Only in Ayoda was he free to tell the truth.

On the other hand, there were those who deliberately restrained their emotions in front of the display, since they were people with a reputation for independence of mind. These said that it was certainly a pity that there would be no procession, but they doubted if the King had much say in the matter. It was probably an intrigue of the Brahmins who held the poor devil (they dwelt upon this bold description of Dasa-ratha) in the hollow of their hands. If anybody asked them, they said, then their opinion, for what it was worth, was that it was all some jiggery-pokery on the part of the new Lord Chamberlain. But others pointed out to these doubters that, Lord Chamberlain or no, the astronomical facts were there, the stars could not lie, not at least in a land where there was freedom of expression. With this argument the doubters were happy to agree.

The crowd dispersed, unanimous in the opinion that being a King was no bed of roses. Even the beggar in the street (they said) had the right to celebrate his own birthday.

V

The Parrot is Explained

MANTARA in her top room had seen the flags; she had heard the trumpets and she had seen the flags come down. But it did not concern her. Her thoughts were filled with the hard and bolt-eyed shell of a bird in its regal cage, and with her good fortune. This she had already begun to enjoy. That is to say, she was in rags, she ate scraps from the kitchen and she was still ignored, but she now loitered in the various courtyards of the palace observing the courtiers as they went about their business or idled during the interminable waits that made up most of their waking hours.

She marked them down. This one turned his head away when she passed. That one did not move his legs as he leaned against the wall of a corridor and she was forced to step over his feet. This one was urinating in a flower plot and did not trouble to conceal himself as she passed. That one pushed her in the back when she was in his way. When she came to power, the man who turned his head away would lose it or pay to keep it in a bag of gold; the man who would not move his feet would move them fast enough under the bastinado; the urinating courtier would spend a year looking after the royal buffaloes where he would be among manners as simple as his own; and the courtier who pushed her would be ruined and disgraced to teach him not to be in such a hurry in going about his business that he forgot the respect due to an elderly lady. She memorised their faces carefully.

But she still did not know just how she would come into her own. The King was still silent about the meaning of her gift. She talked to no-one and nobody came to visit her.

Yet, she had faith that all would be revealed in good time, and so it was.

The two principal royal cooks in the royal kitchen were an ill-matched pair. One was broad and jolly as a cook should be. He cooked the main dishes; he was adept at grinding spices together to make a sharp curry. The other cook was lean and cynical; he looked as though he ate nothing but the other cook's curry-powders. He made the sweetmeats. His skill was unbounded; special boats, straw covered against the sun's rays brought snow by river once a day from the mountains in order that this gloomy artist could chill the froths of milk, sugar, the whites of eggs and ingredients more mysterious that it was the King's delight to eat after his meal. Possibly because the products of his labour were so insubstantial he was devoted, in argument (and the two cooks argued incessantly about everything), to demanding the solid facts. The happy cook took things as he found them (except kitchen boys) and did not find them insupportably bad.

On the day of the proclamation Mantara went down to the kitchen about three o'clock in the afternoon with one of her few possessions, a large wooden bowl in which to put her scraps. The broad and jolly cook was beginning to prepare the evening meal, and the thin cynic was squatting on the floor, surrounded by a basket of two dozen eggs, a heap of sugar on a fig leaf, and an open box of powders that were his own secret. He was looking at these with distaste since he was an artist and like all artists had a profound disinclination to begin his work. The fires in the low charcoal stoves were drawn but the kitchen was hot from the morning's cooking. The two cooks were in a desultory argument, the large curry cook squatting over a black stone on which he was grinding spices with a stone roller. This cook nodded to Mantara in a friendly fashion and indicated a bronze cauldron full of leavings. The thin sweetmeat cook looked at her with such disapproval that she might have been a stick of cinnamon that he proposed to use in the evening's

masterpiece. Mantara ignored him, for she had long ago settled upon his punishment. He was to be put in a dungeon and fed on nothing but sweetmeats until he was as round-bellied as a spoilt poodle. She filled her bowl slowly and listened to their conversation.

"What's really going on, that's what I would like to know," the sweetmeat cook was saying.

"It's all in the Proclamation," said the other.

"*Proclamation!*" said the other, in a tone of deep contempt. "You believe anything they say in a proclamation, don't you? I suppose if one of them fancy young men spat in his trumpet a bit and announced that the King's cook was henceforward and from now on as with effect from today really a woman and not a man you'd give up shaving."

"Wish I could," said the other cook equably, "what with getting up for early market and all, but the Superintendent likes things looking neat and clean. Not that anybody ever wants to see *me*. I could grow a beard long enough to clean a saucepan with before anybody would notice. I haven't seen a member of the royal family closer nor you are to me come, oo, now, it must be five years. Still, it suits me. 'Tisn't my beauty what makes my curries taste, its me turmeric, is what I always say."

"I have," said the thin cook.

"You've what?"

"Seen them."

"Seen who?"

The royal family. One of them, at any rate. I was sent for," said the thin cook meaningfully.

'Was you? Why was you?" said the other with genuine pleasure.

"My mango syrup. That's what she *said*."

"She, eh?"

"That's what I said. Trust a woman," remarked the thin cook in a tone which showed that one should trust her only to do unspeakable villainies.

"Who was it? The Queen?"

"She behaves as if she was," said the other. "No. It was Her Highness, Her Mightiness, Her Who-are-you-and-Spit-in-your-eye Sita."

"Well, she will be Queen one day when Rama gets his turn. They do say they're a happy couple."

"She isn't Queen yet."

"No. You're right there of course," said the other, rolling his spices. "But she seemed a quiet sort of girl to me."

"Ho?" said the sweetmeat cook, sarcastically. "That was when she asked you up to chew over a little *halva* in the boudoir and have a nice chat, was it?"

The other man laughed. "You're the one what moves in high society," he said. "What did she say to you?"

"It wasn't what she said it was the way she put it. Asked me where I was born and if my mother had taught me how to cook. Then she asked me if the Queen liked my mango syrup and how much she ate of it and what else the Queen ate and could she have some like it and would I make her lots of it when she was Queen because when she was Queen she was going to do what she liked which now she couldn't being a stranger and not liking to give orders and thank you she would remember me and here was a couple of pieces of silver so's I would remember *her.*"

"Yes, and what did you say to all that?"

"I thanked her for her money but I give it back to her," said the thin cook with fierce dignity; "I told her I was happy to know she liked my mango but as for what the Queen said and as for what the Queen ate that was Court business. Oh yes, I forgot."

"You forgot what?"

"She asked about Master Barat."

Hearing the name of the Prince that she had nursed, Mantara made an excuse to stay. She asked if she might heat her food a little and being given permission willingly by the curry cook, she stayed, poking and blowing at the charcoal, and she listened.

"Well, now," said the curry cook, turning back to his companion, "what did she say about Barat?"

"She asked if he liked sweets. She asked what he was like when he was a boy and what her husband was like. Then she said: 'The King must have spoiled him, I'll be bound. He's always been the favourite, has Barat, hasn't he?' "

"She's right there," said the curry cook. "I suppose you told her so."

"I told her that so far as I was aware His Majesty the King had no preferences as betwixt and between the heirs presumptuous and aperient," said the cook, and he closed his lips in a hard line like an ambassador refusing to give information that was not covered by his instructions.

There was silence in the kitchen.

"You can see what she was getting at?" said the sweetmeat cook.

"No. I can truly say I don't," said the other, leaning on his roller.

"Think," said the thin cook, impatiently, "what about the proclamation?"

"Ah, yes," said the other, anxious to oblige, "of course." But after grinding in a clove or two he shook his head and said, "I can't remember anything in it about mango syrup."

"*Syrup!* Who's talking about syrup?"

"I thought the Princess Sita was."

"Syrup, huh," replied the other. "She was spreading plenty under my feet but I didn't get stuck. Can't you see what she was driving at? Everybody knows that the King and Rama has had words from time to time. What over I don't know but I can guess it's over that foreign wife he's brought back. And I wouldn't mind betting my year's wages that the King's made up his mind that rather than have a woman like her as Queen he'll make Barat the heir. He can, you know, if he takes it into his mind. So she's starting up a party to support herself and she thought—she *thought*—she'd get me mixed up in it. *That's* why there'll

be no procession. Wheels, is what I say. Wheels within wheels."

Mantara took her food off the fire, put it in her bowl and left without speaking a word. The sign had come. She knew why the King had sent her the parrot.

Without stopping to eat, Mantara went straight to the royal quarters of Barat's mother and demanded admission from the eunuch at the door. He gave her a single glance, held out his pink palm, and when it was not instantly soothed with the touch of money, he rubbed his thumb and forefinger together under Mantara's nose to indicate what he wanted.

Mantara had no money. But she did not argue and she did not hesitate. She was sure her moment had come: had the eunuch demanded her bloodshot right eye she would have given it to him. So now she waddled as fast as she could go back to her own turret and took the dead parrot out of its cage. She blew the dust off it, stroked it and apologised.

"When I have done my work," she told it, "I shall give you a cage of gold wire with a perch of lapis lazuli and two servants to look after you for ever. Just now I must give your cage to the eunuch because I must see Barat's mother."

She put the parrot carefully among the rags which made her bed, where it lay with its head on a greasy cushion, its beak gone scaly and green from the poison with which it had once been anointed.

The eunuch examined the cage in detail breathing through his nose and letting his fat lips fall open. At length he nodded and walked away from the door, his bribe swinging from his finger. He disappeared down a corridor leading to the eunuch's quarters and Mantara, left alone, pushed open the door and went in to see her old mistress.

The Junior Queen was lying on a round bed that stood a few inches above the floor and had a fence of pierced silver to hold in the cushions. She was forty, with what remained

of her youthful and fragile beauty after years of irritable bad temper. She lolled on the bed with the utter weariness of a person who has done nothing whatever for a lifetime.

She looked up petulantly as Mantara entered. She recognised her immediately, although she had not seen her for more than a year. She had a capacious memory for people against whom she could complain.

"Mantara," she said and fidgeted with her bangles. She nodded permission for the woman to speak.

"Your Majesty," said Mantara, and creaking down to her knees, she touched the Junior Queen's painted toenails as they lay curled in the cushions. "I have come . . ."

"You have taken your time."

"Your Majesty did not summon me."

"Am I a magistrate?" asked the Queen. "Must I send the guards to everyone I want to see? Can nobody come to see me because they are fond of me?"

Mantara bowed her head and holding the lobes of her ears shook her head slowly from side to side, in the immemorial Indian gesture of contrition.

"I have been ill," she lied.

In this palace of lies, illness was the customary one, and passed for an apology. The lie was necessary. The Junior Queen had begun her life as the pretty daughter of a small country nobleman. She had early shown that she had two fixed aims in her life: she wished everyone to love her, and she would do nothing whatever to make them do so. When she was twelve her mother explained to her that this attitude had no sense; at sixteen she was told angrily by her father that it would lead to her ruin. At seventeen she was taken to Court. When the King became fully aware of the depths of her feminine selfishness, he fell at her feet and after grovelling there for some time, married her. She became Junior Queen and neither her mother nor her father nor anybody else criticised her behaviour again.

"Well, then," said the Junior Queen to Mantara, "so you have been ill and now you are well so what do you want?"

"I want to save your Majesty."

"From what?"

"From being ruined and despised and sent to live in the backroom of these quarters."

"Despised?" said the Junior Queen. "I think I shall slap your face. People do not use that word to me."

"Not now, Majesty. But when the King dies and Rama rules, his wife, Sita will be queen and you will merely be the mother of Barat, a younger son."

"The Princess Sita is an honourable woman. She will know how to behave towards me."

"Yes: she's already plotting it."

"Plotting? With whom?"

"The pastrycook."

The Junior Queen laughed very heartily at this. But she listened to what Mantara had to say intently.

Mantara lowered her voice but after she had been speaking for some while, the Junior Queen feared that even her muttering might be heard. She drew her into a corner and bolted the door. The two women huddled closer.

"But my brooch is not a parrot," protested the Queen, after some time.

"Your Majesty must be mistaken."

"No, I'm not," said the Junior Queen. "It is a hawk. I remember the King telling me so when he gave it me."

"Then your Majesty is quite right to say it is a hawk but it is the King who was wrong," persisted Mantara.

"Well, let us look at it," said the Junior Queen.

Hearing a noise outside the door, she opened it slightly and sent the eunuch away on a long errand. Then she went to her jewel box which stood on four small wooden antelopes in a corner. She searched, rattling the jewels until she produced a small brooch.

It was shaped like a hawk.

"There," said Mantara, "it's a parrot."

"How *can* it be?" said the Junior Queen, pointing to the bird's head.

"It must be," said Mantara, "or else the King would not have sent me a parrot; he would have sent me a hawk. He wanted me to remind you that he had given you the brooch."

The Junior Queen giggled as she looked at the hawk.

"I've never told anyone why he gave me it."

"You told me," said Mantara.

"Did I?" said the Junior Queen. She giggled once more, and Mantara did the same until a fit of coughing overtook her.

King Dasa-ratha, they recalled with looks and winks, had given the Junior Queen the brooch after her wedding night because their embraces had been disastrous. The King, for once, had become impotent. He had made a royal gesture to cover his confusion.

"Anything I wanted I could have, he said," the Junior Queen whispered. "I'd only to show him the brooch."

"Then show him it and ask for Rama to be thrown over and your son made heir. He won't refuse," said Mantara. "It's what he wants, don't you see? He wants an excuse. Barat's always been his favourite."

The Junior Queen hesitated.

"But suppose," she said, "suppose—it's a long time ago—that he doesn't agree—suppose he won't keep his promise—suppose . . ."

"Then let him know," Mantara answered, "that you'll tell everyone in the Court the story of why he gave you the brooch."

The Junior Queen thought for a while. Then she giggled once more. She said:

"Yes. *That* will do it."

VI

Intrigue and Innocence

THE assembly was of the utmost splendour; the King was positively seen to weep; Rama turned a pale ivory; and all the Brahmins agreed that his behaviour subsequently was a credit to his education. It was, in a word, an historic occasion.

Having summoned Rama to the Audience Hall, King Dasa-ratha received him with every mark of affection. He seated him on a stool on his right hand, next to the low throne on which he himself sat crosslegged. He put his arm round his son's shoulders and asked tenderly after his health, and while Rama answered, the King, plainly with his thoughts on the sad duty to come, shook his head that looked like half a melon from side to side.

Then an usher, his long hair richly oiled and a garland of flowers round his neck, waddled to the entrance of the Hall. He came back shepherding a man and a woman both dressed in Brahminical white but poorly. The usher prodded them officiously with his ivory stick of office until they were exactly opposite Rama and the King. He then gave the man a sharp tap on the shoulder and the two poor Brahmins fell prostrate at the King's feet. That they omitted the usual crawling on the marble, and that the usher permitted them to do so, showed that they were no usual suppliants.

The King rose. Rama rose. The King held up his hand. The two Brahmins got to their feet and Rama could see that they were an elderly man and woman, both of a mild aspect, and both frightened. The King began to speak and as custom demanded, Rama listened to his father with bowed head.

"Son," said the King, "dearly beloved and inheritor of my sceptre, your father humbly begs your forgiveness." At this

the King bowed his own head towards his son, and stood holding his ears in contrition. Generous tears started to Rama's eyes and he protestingly murmured that a son could not forgive his father but only obey him; but if a son could, then it was done.

"I am grateful," said the King, "and now I may speak freely." He turned away from his son, not without showing some signs of relief, and, while addressing him in his form of words, in his posture addressed the Court, in particular the scribes who, sitting crosslegged against a pillar, made notes for the Court historians who would later work up the King's words into the Chronicle of the Deeds of the King.

"Dearly beloved son, you know that in my youth I went hunting, one ill-omened day, and I was led away from my companions by a deer of exquisite beauty. I chased it for many hours and even when the sun had set, I followed it, contrary to the prescriptions of our holy Brahmins who say that we should put aside worldly concerns at the onset of night, and pray."

Here there was a murmur of approval from the Court Brahmins and the King proceeded:

"I followed this animal along the banks of a river and I would not give up the chase even when it was almost night. Then I heard it, as I thought, stop to drink. I loosed off an arrow through the reeds, blindly, shooting at the place from where the sound had come. I heard a great cry of pain. But it was not the cry of an animal. It was the anguished voice of a boy."

Here a profound silence fell on the Hall of Audience, although everyone present knew the story well. The man and the woman bowed their heads. The woman put her hands to her face and it could be seen that she was weeping. If the silence of the courtiers was a mere politeness, no-one could doubt the genuineness of the woman's grief.

"I had shot a young lad," said the King in a lower voice. "A fine boy of fourteen years lay in the water that was

reddening with his blood. He was the son of this simple and holy man and this simple and holy woman. I took him back to their modest house which he with his last strength, pointed out to me. He died in his father's arms within the hour."

The King lowered his eyes and bent his head. His scant curls, artificially lengthened, swung forward and hid his cheeks. He looked up. The curls returned in disarray and underlined the King's unhappy knack of appearing an ageing woman.

"Is this true that I have said?" the King asked the father. He did not answer but a sharp tap of the usher's rod brought him to his senses.

"Majesty, it is true."

The King turned his rounded nose and receding chin upon Rama and looked on him with his exhausted eyes.

"I told them that I was a King. I swore that I would make any reparations which they asked of me, short of my Kingdom or my life, which were given me by the gods themselves. The father asked only one thing: that as I had taken away their eldest son whom they had cherished fourteen years, my eldest son should be taken away from me for the same time; and that it should be done when I stood, as he did, on the threshold of old age. I had no son. I consented. I am now fifty years old. They are here to claim the fulfilment of my royal and sacred oath."

In the spandrels of the arches that rested upon the columns of the Hall of Audience were grilles of stone, from which the ladies of the Court and their women could watch in decent seclusion the ceremonial below. The Junior Queen leaned her face against one of these: a few feet away Mantara peered through another. Now, as King Dasa-ratha repeated the vow he claimed to have made, the Junior Queen stretched out her hand, tugged Mantara's sari, and then tapped the jewelled hawk, winking and grimacing.

Below, Rama, white with dismay, was protesting that he

had always thought that the King had vowed a temple in reparation and that he had rebuilt it and that . . .

"You were not born for two years more," said the King, his irritability showing through his stately manner, "I wished to make some gesture of my grief that would be immediate. But the vow stands. And they claim it now. That is true?" he said turning to the man.

The gentle old man raised his eyes and looked at the King in terror. He licked his lips.

"Yes," he said.

The King nodded his half-melon of a head briskly. "Dearly beloved son," he said, and now his impatience was plain, "you will want me to break my oath. Say so now, with the greatest Brahmins in the land as witness, and in front of this old woman and this old man, so that they may go away and trouble me no more, and so that I may go to my death and face the penalties which the Gods will inflict upon me for my murder and my broken word. Speak!"

But Rama, folding his hands in front of his face in a gesture of respect, bowing his head towards his father, repeated the lesson he had been taught since his childhood.

"The word of a King may not be broken. The duty of a son is to obey."

With that he fell silent, but bowed still deeper. The King said nothing, and Rama, his voice trembling, asked the King's permission to withdraw.

The King unwillingly agreed, first glancing across at the Lord Chamberlain, who nodded his head in approval of Rama's request.

Rama descended to the floor of the Hall of Audience, paused, did reverence to the parents of the boy who had been killed, and then, his head still bowed and his face bloodless, he left the audience chamber.

Rama first asked advice of his tutor, a small Brahmin with a schoolmaster's mind, who had taught him to read, and to be a good boy.

The tutor was a man of the highest ideals, who lived in constant fear of being without employment. He loved his pupil Rama, but he was aware that a man of twenty-seven does not need a schoolmaster. Rama had no children: the King had more than he could count.

He advised Rama that a father's oath was sacred to son and father alike; he sang several Sanskrit texts to prove it, not failing to point out the interesting points in the grammatical structure of the sentiments as he did so. He suggested that Rama spend fourteen years in China, studying.

Next Rama asked advice of his personal priest, the Brahmin, who tended his altar fire. The Brahmin had accepted the post in the hope that he would be in the centre of court intrigue and thus secure his advancement. Rama never intrigued and the Brahmin despised him. He told Rama that a man who caused his father to commit a crime would be tormented by devils for all eternity in Hell. He advised Rama to go to Magada and throw himself on the mercy of its ruler. By playing his cards well, said the Brahmin, he might collect an army and return with something to say for himself.

Next Rama asked the advice of the Lord Chamberlain. The Lord Chamberlain was privy to the plot and had already made good his post with Barat. He told Rama that he thought no young man should be loaded with his father's mistakes. However—and here he lowered his voice and spoke in a very round-about fashion—however, the King's weakness for ladies had got the monarchy into bad odour in the city. If it were known that the Royal family condoned the killing of a Brahmin and broke its sacred word, the reputation of the monarchy would suffer still further. The monarchy should set an example to lesser men. A prince had certain advantages—certain responsibilities, as well. For the safety of the State he advised Rama to leave the Kingdom. "Try a trip to Malabar," he said, "the scenery I am told is superb and the hunting in the Nilgiris is not to be equalled." He overreached himself here, for Rama,

uneasily suspecting that the Lord Chamberlain was treating him not as a man with a moral problem (as he felt himself to be) but as an idle-minded boy, protested:

"I cannot spend fourteen years hunting."

The Lord Chamberlain recovered himself.

"Fourteen years, Your Highness? That is a very long time. In the life of a great prince like yourself, *one* year is a long time. Who knows? The King may die—the gods forbid, of course—or I, even, may see some way—who knows—some reason—of State, naturally—to accede to a popular demonstration, shall we say, demanding your return—ah, hum, a *spontaneous* demonstration, of course."

"Do you think that they will?"

"I am practically certain they will," said the Lord Chamberlain. "I only regret that it's impossible, for political reasons, to organise a spontaneous demonstration this very night. But—well, you understand these matters even better than I do."

Rama understood nothing, but he nodded sagely. He should not be blamed. The middle-aged flatter the young for no purposes save their own—but only the middle-aged know it.

The Lord Chamberlain thought of taking his leave, but stayed to ask one question.

"And what does Your Highness mean to do tonight?"

"I shall sacrifice on my altar," said Rama, "and I shall supplicate the gods to guide me."

"Good," said the Lord Chamberlain, solemnly. "Very good." He was reassured for he knew that a man of action offers Thanksgivings, but never supplications. He was now convinced that Rama would give him no trouble. He said, in an offhand way:

"His Majesty asked me if I thought you would be able to give an answer by morning tomorrow and I said that I thought that a true nobleman like yourself with your great intelligence wouldn't need as much time as that to do his duty."

"Of course, of course," said Rama unsteadily. "To-morrow morning then. Duty, yes. That's simple, as you say. But it raises questions: so many questions——"

The Lord Chamberlain, satisfied, settled himself down to what he shrewdly estimated would be about ninety minutes' listening. He did so amiably. He was a man who did not believe in hurry unless there was something to be got for himself: and he had got all he wanted.

Now Rama was a young man of fashion and the fashion among young men of his (and less distant) days was to roll notions round their minds and to ask tremendous questions about life: a proper thing to do because the history of mankind is moulded by their ideas and a fine spectacle it is.

Rama wanted to know what his purpose was here below: to do his duty by the gods? to do his duty by himself? or to be free? He wanted to know if as a prince he should do what he thought would be good for his subjects, or what they thought would be good for themselves; or something of each; or to build heaven on earth? He wanted to know if his destiny was more powerful than his free-will, if he should control his appetites, or educate them, or suppress them, or indulge them without stint? He wanted to know if he ought to strive to be a great man, a humble man, a practical man, or a saint? Was the world real? Or an illusion? What was man doing here? Should he rejoice? or despair? Was he damned? Could he be saved? How? Was the way of renunciation (which was attracting so many of the best minds of the day) the right way? Should he seize this chance to give up the world?

All of these were good questions and only a cynic would say that they have never been answered. But it might be said that they were difficult to answer between supper and breakfast.

When the Lord Chamberlain rose to go, he said:

"I am out of my depth with a brilliant mind like yours. But I leave you with this thought. Renunciation, say all the

sages, is the path to liberty. And if a prince became a hermit he is sure of being famous throughout the land."

The Lord Chamberlain bowed and left. He had made up his mind that Rama was generous, warmhearted, loyal, well-meaning, intellectually brilliant, idealistic, and a damned fool. In this he summed up the general opinion and this was only to be expected for that is the major art of being, as he was, a successful politician.

VII

Sita

THERE were two people in the palace who did not think Prince Rama a fool. One was his brother Luxmun and the other was Sita his wife.

Sita was a young woman with an oval face, long eyes shaped like almonds, a slender figure (but she was rather short) and a graceful carriage when she walked. She was otherwise quite unremarkable. Because of this she presents a insoluble problem for anyone re-telling the ancient story of Rama.

Whether we take the story as altered by millennia of Brahminical forgery, or whether we take the bare bones of the tale which is all that we can be sure is original, there is no doubt that Sita is the heroine.

But Sita was not heroic. She was perfectly satisfied with loving her husband, and this, with a husband as handsome as the young Rama, did not call for heroism. She was never torn with anguish—she was too busy looking to Rama's comfort. She was never seized with the desire to revolt from the bonds of marriage—she would have considered it as silly as revolting from being, as she was, just under five feet high. She was not determined to make her husband a famous man—she looked upon all other men as unfortunate failures beside him. She was not passionate; she merely enjoyed being in bed with her husband. She was faithful, but not dogmatically so, as we shall see. She was not proud, except of her husband; she was not imperious except with her dressmaker; she was not mystical, except when doing arithmetic. She had none of the qualities of an Indian, or any other heroine. She was a good woman, a good wife, and a simple soul. We must put up with her.

Luxmun, Rama's younger brother, can best be described

as a good companion for her. He was strong in body, and wore large mustachios. His moustaches and his brother were the things he loved most in the world. Next, he liked a good fight, but a fair one. He thought of himself as a soldier and had been through a campaign or two, in which he had shown courage. He was brave, honest, straightforward and, again, a simple soul. His unsophisticated face behind his unsmart moustaches appears in the background of all Rama's adventures. We must be content, therefore, with two good and uncomplicated people.

They sat together now outside the room in which Rama was meditating his decision.

Luxmun put his hand on Sita's. She smiled up at him briefly and then returned to her watch upon the door which she had maintained for two hours.

Then a servant came in with a cup of hot syrup. Sita took it, and tapping gently at the door, went in to her husband.

Luxmun waited, pacing the room with a military stride and biting his moustaches. Once he yawned (for he was young and the night seemed endless) but he rebuked himself and bit at his moustaches more savagely to keep himself awake.

After a long quarter of an hour Sita came out. She set the empty cup down on a small table.

"Well?" said Luxmun, keeping his voice low lest his brother should be disturbed. "Has he decided?"

Sita nodded. She smiled at him again, but uncertainly. "It seems," she said pulling the head piece of her sari forward, "that we are going to renounce the world."

"When?"

"Tomorrow morning."

"Does he know that we mean to go with him, whatever happens?"

"I told him so."

"Did he forbid it?"

Sita paused. She sighed.

"I think, brother-in-law," she said, "that my husband is

in such a wonderfully elevated mood that he won't notice whether we are with him or not."

"Oh," said Luxmun, "well, good, then."

"Yes," said Sita. "I suppose it is. Well, I must go and put a few things in a bundle."

"Bundle?" said Luxmun. "Well, I don't know about that. Never seen one of these fellows who's renounced the world with a bundle. A stick, yes. And a bowl. But they never carry a bundle."

"Oh," said Sita. "I've never noticed much myself. But I'm sure you're right. Well, then, I must go and pack it."

"The bundle, you mean, Sita?"

"Yes, Luxmun."

"But, Sita, as I said, they don't carry one."

"Never mind," said Sita, "*I* shall carry it."

"Yes, of course. Or I could," said Luxmun.

"You'll have your bow and your spear. He'll need protecting. And I don't care whether the others do or not. You'll have to take care of my husband."

"I shall, most certainly."

Sita looked at the door reflectively.

"It's strange. To think that he'll be a great saint."

"Always knew he'd be a great *man*," said Luxmun, also looking at the door. "I'd rather hoped he'd be a great king."

"To renounce the world," said Sita firmly, "is a far finer thing than being a king."

"Yes, of course," said Luxmun.

"Well," said Sita. "I'm going. Aren't you going to bed?"

"I think I'll wait a little."

"Then, goodnight Luxmun."

"Goodnight, Sita. The gods keep you."

Thus, unheroically, they parted.

VIII

The Noble Gesture of Prince Rama

THE news that Rama was going into exile to fulfil a sacred pledge of his father's stirred the whole town. People wept openly in the streets. Everybody felt uplifted. They all felt that they, too, were really capable of such a noble deed, if it were not for their wives, their children, their debts, their mistresses, their businesses, or their rheumatism. The early morning beggars did very well; a merchant informed a customer that he had paid too much by mistake; men going home from the brothel quarter and hearing the news in the hot-drink shops, determined to rescue at least one woman from her life of shame. It was as though an angel had passed through Ayoda, brushing the inhabitants with the tips of its wings.

"They'll be looting the shops by ten o'clock," said the Lord Chamberlain to his barber as his spies briefly reported the morning gossip of the town. The next hour showed signs that he was right.

The sentiments of the people changed. From feeling that they all could do so noble a thing they turned—as the press of daily affairs grew worse—to saying that not even Rama should be asked to do it. They were being robbed of a future king and a king such as history had never witnessed. All knew the story of the dead boy: nobody until now had heard of the oath. Those who had wept in the streets dried their eyes in the hot-drink shops and took a realistic look at the matter. While praising Rama as a saint they had to agree that he was a simpleton. Something, they said, was going on behind the poor boy's back, and it boded no good for the people. There was a woman in it, they'd be bound. That was where the taxes went, on women.

The sun rose higher and so did the indignation of the

people. The beggars got no more money, a loss which they accepted with philosophy: in common with priests they had every reason to know that religious fervour changes men's lives, but not usually for very long.

Sweating deliciously from their spiced hot drinks, the more fiery members of the crowd began to make for the tax-collector's booths. The tax-collectors, having prudently put up their shutters, the crowd wrote RAMA across them and then, somewhat inconsequentially, smashed them up. They were shouting outside a rice store when the Lord Chamberlain strode to Rama's quarters, bowed to the ground and begged him to save the situation.

Rama was in a state of exaltation, partly from lack of sleep and partly because of his decision. He was quite unable to follow why his resolve to take the saffron robe (the mark of renunciation) should lead to the sacking of food stores. The Lord Chamberlain fervently assured him that there was an explanation but the time consumed in making it would cost the town at least two rows of shops. He begged Rama, out of the nobility of his spirit, to show himself to the people dressed for the hunt, and so reassure them that he was not leaving.

Rama replied reasonably that since he had made up his mind to go he did not see any purpose in leaving disorders behind him. But a question occurred to him, and this time it was not one to do with the Universe or his soul. He said:

"Last night you spoke of demonstrations in my favour. This is one, then?"

The Lord Chamberlain had forgotten what he had said the night before, a habit which he had cultivated. As a rising politician he had hoped that what he said would always be memorable: as a mature one he depended on it being the reverse.

"That," he said, "was different." And then recalling with an effort what he had said, he went on triumphantly, "These are hooligans."

"I understand," said Rama. But he did not understand,

and for the first time in his life, he knew that he did not. It was the beginning of his education in living.

The world had never looked so difficult to renounce as it did that morning. By the Lord Chamberlain's guileful forethought, Rama's chariot was ready for him, and it was in this that he drove to the confines of the city. Crowds gathered round his horse: women threw flowers: old men called blessings and some younger ones shouted remarks against the King.

But the soberer heads among the citizens, those who could stand back and take a steady look at things, pointed out that there was one clear proof that the rumour of the Prince's exile must be false: nobody would go on a long journey into the countryside by chariot. With the roads what they were he would have to abandon his chariot in the first five miles. Plainly Rama was going hunting in the woods outside the walls. These sensible citizens joined in the cheering good-humouredly, and then went home quietly, advising everybody else to follow their example.

The shouting died away, the cheering subsided, and there were no more flowers. Rama drove through the city gates, surprised at finding how pleasant the tribute had been, and surprised, too, at himself, that he should think so.

Half a mile beyond the gates of the city, the road passed through a wood and there Rama found his wife and brother waiting for him.

Now came his most testing moment; now he must send back the charioteer and his horse and chariot; now he must renounce the pleasures and power of the world.

The cheering still sounded in his ears: he could still smell the scent of the flowers as they had been crushed beneath the hooves of his horse.

He reflected as he patted his horse's neck that nobody had ever taken that amount of notice of him before. He reflected again, as he gave the charioteer a ring from his finger as a keepsake, that they had only noticed him because he decided

to uphold the honour of his father and to show himself a dutiful son, and because a father's honour and an obedient son were the foundation (so said the Brahmins) of all society and all religion. He had roused the city by his noble gesture. He would not betray it. He dismissed the charioteer.

But Sita and Luxmun noticed that he watched his horse until it could be seen no more, and that when he turned to them and said that he was ready, he was crying.

He walked ahead. The others fell in behind.

"Shall I tell him," whispered Sita, "that I've got his hermit's dress in the bundle?"

"No," whispered Luxmun. "Not now."

So Rama began his exile dressed in the trappings of a princely hunter, seeking, not game, but answers to his questions.

The hermit's saffron robe remained in Sita's bundle through the spring, the hot season, the rains and the cool weather—the better part of a year of wandering. At the end of this period Sita gave the robe away to a necessitous hermit.

This did not happen because Rama was unwilling to become a holy man, but rather because of the reverse. Rama had conceived the notion of having the robe put on him by some saint who, having answered his questions, would welcome him into the community of the elect.

In the course of his travels he met several saints who were very ready to welcome him but were not so warm towards his questions.

The three journeyed from holy place to holy place, not only for piety but also for shelter, there being no other places in which to rest in the countryside. Their approach to a holy place would be heralded by gossiping peasants, who had met them on the road or had seen them at their last halting-place.

The holy men would come out to greet them with garlands and edifying hymns and invite them to a meal. The holy men were all Brahmins of the most orthodox variety,

and in the Brahminical version of Rama's history that remains to us, great space is given to describing them. Their holiness is extolled, their courtesy magnified and their edifying hymns included word for word. After the meal, the three pilgrims would retire to rest. In the morning Rama would respectfully ask his host to instruct him in the path of renunciation, after which he would beg leave to ask a few questions. In a matter of days the three voyagers would be travelling again with the most urgent and pressing introductions from their host to the next holy man along the road: who, having withstood the questioning as long as he could, would resort to the same device.

In this manner Rama, Sita and Luxmun arrived at a riverside holy place where the saint had just died. Having assisted the villagers at his cremation, they were at a loss for where to go. The headman of the village, awed by the plain signs that his visitors were high born, knelt and touched their feet. With great hesitation he told them that some few miles along the bank of the river there was a hermitage. When pressed by Rama to say whether any holy men lived there, he begged to be excused from answering. It was called, he said, the Hermitage of the Gluttons.

Rama, Sita and Luxmun set out with many misgivings, hoping to find some more promising halt on the way. But the road, although beautiful, was deserted, and all day they passed no sign of habitation. Towards four o'clock they came within sight of the Glutton's Hermitage, and Rama, cautiously exploring it, met the man who was to make his name and his adventures famous—the exiled poet Valmiki.

BOOK II

The Tales of Valmiki

I

The Hermitage of the Gluttons

VALMIKI was the first author in all history to bring himself into his own compositions. This was a remarkable thing to do. If you take pleasure in reading books, whatever your race, you should do honour to the memory of Valmiki. In the sunrise of writing he established the fact that a book is written by an author and not by a committee of accurate grammarians. Valmiki insisted that he was somebody, although in fact he was a nobody. The least-important Brahmin who screwed taxes out of the peasants who sold onions in the market-place was more important than this disgraceful scribbler who was not even allowed to live in decent society. But Valmiki did not think so, and he put himself into his story, as bold as brass. I think that he even began the story with himself, although in the texts that we have the Brahmins have written in a few preliminary chapters to make things more respectable. But they did not suppress Valmiki. They left him in the story, merely altering his opinions.

But civilised mankind, in its morning hours, had more than one Valmiki. There was a whole sect of men who, disgusted with Brahminical subtleties, Brahminical tyranny, and the Brahminical love of philosophical argument—by which they proved that everything they did was right because God said so—had gone off into the forest and set up a hermitage. They called their sect the Gluttons, because (they said) a man lives by eating: or, rather (they argued), by observation they had established the fact that when a man does not eat, he dies. Whatever gods there be, one of them must be in a man's belly and they sacrificed to him three times a day—or, in the case of the more devout members of the community, four times. They were soon joined

by other sceptical people who had fallen foul of the Brahmins, and among them, it would seem, was Valmiki. There is no evidence that he was an official Glutton, but he evidently found their company congenial because he put one of them into his book.

While Valmiki was living in this hermitage Prince Rama arrived there and the author gave him shelter. It was then that the idea of writing the life of this unfortunate prince arose in Valmiki's mind.

The hermitages at which Rama and his companions had previously stayed had been uncomfortable and squalid. This was because the hermits who lived in them wished to be holy. When Rama and his companions came upon the Hermitage of the Gluttons they found it neat and clean and pleasantly disposed between a half-circle of hills and the bank of a considerable river. This was because these hermits did not wish to be holy; they merely did not want to be wicked. People so lacking in warmth and enthusiasm must be content with their own company, and the Gluttons, having quarrelled with the Brahmins, had set up the hermitage to make this possible in a convenient and inexpensive manner.

The houses stood well apart in a half-circle that followed the sweep of the enclosing hills. They were made of clay and thatched with the dried leaves of palms. The ground rose gently behind each of them, and it was terraced. On the terraces grew fruit trees, flowers, and vegetables. The space in front of each house was sanded and paths led from each sand-patch to a banyan tree that grew near the river. Its wide-spreading branches and the roots that grew down from them in thick columns made a meeting-place. There was nothing else. No house was bigger than the others: all had one storey. The men lived in perfect equality, none was jealous. Since there was no jealousy, there was no rivalry. Since there was no rivalry, everybody did much the same as everybody else. The community was harmonious, since

nobody would have cared a rap if it had broken up the very next day.

Valmiki had been the last to join them and his house was therefore on the tip of the half-circle. Thus Rama, coming into the settlement, approached this house first.

He signalled to his two companions to remain behind, and he himself strode into the middle of the sanded place in front of the door and he rested upon his great bow.

This weapon was six feet long and rose just above Rama's shining black hair. It had two sinuous curves, and in the middle a handgrip of silver, chased with designs of antelopes. It was a bow that could be drawn only by a man of great strength: it was a bow that could be controlled only by a man whose strength was disciplined; and such was Rama, after his months of pilgrimage. His skin was a golden brown and gleamed with the movements of the muscles beneath. His torso, naked save for the strap that bore his quiver, was heavy shouldered and greatly narrowed at the waist, in the manner most admired among Indians. The pleated cloth around his hips curved over buttocks that were something womanish, a sign in his race of high breeding. It fell half-way down his thighs, which were strong and spare. His feet were now shod with country sandals, made of the hide of a deer. He wore no ornaments, so that nothing beguiled the eye from the astonishing beauty of his face.

Down the centuries the face of Rama has never been forgotten. Sculptors have handed on the memory from generation to generation and from a thousand statues each differing a little, we can derive his true portrait. He had long eyes. His nose was thin and flaring: his lips rich: his chin that of a boy. There was nothing arrogant in his expression, but the carriage of his head was very noble. He moved with grace and spoke with a voice of a man who is accustomed to being heard with attention. Apart from the sum of all these attributes there was something more—an air of freshness, a clarity, a directness, as of a young man coming in from a fine hunt on a glorious morning. At the time when

he met Valmiki he was twenty-eight years old and still rather simple for his age.

As a sign of peace, he unstrung his great bow with an expert gesture. He then looked around him for the owner of the house and found him at work on the terrace above, pruning a tree.

"Reverend father," called Rama.

The man looked round. Then the man nodded, and hitching up his loose robe, came down some stone steps that joined the terraces, alternately looking at Rama and at where he placed his feet, so that he stumbled a little, and made anything but an impressive descent.

When he had reached the sanded area, and come nearer, Rama could see that his hair was greying, although he was not in any way infirm. He was well-built, but bowed in his shoulders, and had no repose in his movements. He gave Rama a friendly but very keen glance.

Rama saluted him by raising his joined hands and bowing his head.

"Reverend father," said Rama, "I ask you to grant me and my companions shelter. We are strangers."

"Yes, yes, certainly," said the owner of the house quickly. "Strangers are always welcome. It's my old friends who aren't. They come here and lecture me on my bad habits and go away with a basketful of my best artichokes."

As he said this he grinned. This grin was the most remarkable affair, and it was largely responsible for his having innumerable enemies. It was so striking that anybody watching the two—the stalwart Rama and the round-shouldered poet—and observing the grin would immediately forget Rama, his deep chest, his great bow, his correct buttocks, and his strong legs; all would be shadowed—if a grin can throw a shadow—by this phenomenal expression on the face of the older man.

The setting for the grin, Valmiki's face, would have commanded respect but not interest, and certainly not hostility, if it had been devoid of this feature. In repose

Valmiki could be seen to have a high forehead, a narrow face, and a long nose dividing large eyes that were full of intelligences. These eyes were heralds of the grin. They shone, glittered, and appeared to change colour. Then the poet would smile; the smile would make two deep creases from his nose to his jawbone and a myriad smaller ones at the corners of his eyelids; and the smile would expand and blossom into a grin, and this was so redolent of comedy, of satire, of amusement and suppressed laughter, that the watcher found himself smiling, or laughing aloud, as though the world had become a clearer and enlightened place, as though much that was dark had been mysteriously explained and a great many fears had been shown to be bogies: that is to say, if the watcher were young. If he was older than forty he felt, usually, as comfortable as a thief in the beam of a lantern.

"May I call my companions?" he asked.

"By all means. And who are they?"

"My wife, and my brother."

Valmiki, grinning once more, said:

"Then you are, of course, Prince Rama, the famous young man who has been thrown out of Ayoda for his crimes."

"I am a pilgrim seeking the path of renunciation," said Rama. "I was not thrown out of Ayoda, I was . . ." He paused and searched for the right words; he found it difficult to find them under the scintillating gaze of Valmiki. "I was asked to leave," he said, a phrase which he could not help feeling was unsatisfactory. "In any case, *I*, at least am innocent of any crime."

"Except," said Valmiki, "that of being handsome, generous, and a loving son, and of having a devoted wife and a faithful brother. I wonder that they let you escape with your life."

"Then you know Ayoda?" said Rama, and once again felt that there were better replies.

"Yes," said the other. "I am also an exile from your city.

My name is Valmiki. I, on the other hand, committed four thousand crimes, each of them without a single professional flaw. Go and fetch the lady, your wife, and His Highness your brother. I will go in and make the house ready to receive you."

Rama bowed hastily, full of the gravest doubts. He returned to the road that led to the hermitage. He found his wife sitting in a dispirited manner on the root of a tree and his younger brother leaning wearily on a spear. As Rama approached, his brother straightened; he gave his sister-in-law an encouraging pat and his own large moustaches an upward twist. "Here he comes," he said to the woman. "We shall soon be able to rest ourselves." But when he asked his brother if he had found shelter Rama shook his head.

"No, Luxmun," he said. "I do not think so." He looked at his wife with great gravity.

"Has he turned us away?" she said, and she pushed the hood of her sari from her forehead and sighed. The sun, although it was late afternoon, was still very hot and they had walked many miles that day.

"That is the difficulty, Sita," said Rama. "He has made us very welcome. As for me, I wouldn't mind taking the risk and spending a night there . . ."

"Risk, eh?" said Luxmun, eagerly. He shifted his grip on his spear.

"But I cannot allow you to do so."

Sita lowered her head in obedience; such, the Brahmins taught, was her duty as a wife. She also determined that come what may, she would sleep in the hermitage that night. This was her duty to herself as a woman, about which the Brahmins taught nothing because they knew nothing.

"The man's name," said Rama, "is Valmiki. I remember being told by one of my instructors that he was a murderer."

Sita raised her face in alarm at this, and even Luxmun showed uneasiness.

"Yes," said Rama, "I was told that he killed a Brahmin."

"Oh," said Sita, calm again, "that is a very terrible thing to do, of course."

"Of course," said Luxmun, once more resting easily on his spear. "But then none of us is a Brahmin."

"And I have very sore feet," added Sita.

"He says," went on Rama, "that he has committed four thousand other crimes."

"That is a *very* large number," said Sita. "The surprising thing is that he has been able to keep count of them. I think I should be more frightened of a man who had committed one crime than a man who says he has done four thousand."

"Besides," said Luxmun, "they are probably old woman's crimes, like not finishing his prayers. These hermits grow very odd in their ways."

"And," said Sita, "I do not think I could walk any further, unless you ordered me to do so."

"Perhaps we could try some of the other houses," said Luxmun, "but since I can see him waiting at the door, he might be offended if we did and lay a curse on us. In fact, I think he will curse us in any case if we keep him waiting much longer."

"And I was always told," said Sita, "that a hermit's curse was a very awful thing. So perhaps we had better say a prayer for the Brahmin he killed and hope he soon gets out of hell, although of course being a Brahmin he wouldn't be in hell, and go at once."

Rama, who as the eldest of the party, felt his responsibility for them, hesitated.

"I think," he said, "I remember being told by a Brahmin that this Valmiki was a poet."

"Very well," said Sita, "if he starts talking poetry I shall get up and leave the room."

"And I shall hit him once or twice with the blunt end of my spear," said Luxmun. "So that is all settled. Brother, please lead the way."

Rama did so, and Luxmun followed one pace behind and Sita five paces, according to the rules of propriety that their

Brahminical tutors had impressed upon them when they were little children. According to these rules, no-one could walk side by side with a prince, unless he were a Brahmin.

They eyed Valmiki cautiously as he made them welcome, but for a criminal he was very well-mannered. He led them to a clean bare room where a boy waited with bowls of water, and when they were seated on mats of dried palm leaves, the boy washed their feet, not keeping his eyes on the ground while he tended them as he should have done (being, according to the Brahmins, an inferior being) but looking them in their faces, and even speaking to them.

The impertinent boy then served the meal, which was a simple preparation of fruits and vegetables. This, at least, was proper for a hermit, and they began to eat freely. Valmiki's way of saying grace was, however, very much his own. The grace that the Brahmins said for Rama in his palace before joining him in his meals, was long, sonorous, and thanked a battery of gods by name for their favours. Valmiki said:

"Gods in your heaven grant that we eat this meal remembering that we may die this very night and never taste such good things again. Sweet gods, fatten the pumpkins. I've done all I know and just look at them. So be it."

Nothing very much was said during the meal. Valmiki's attempts at conversation were turned aside by his guests. It was not etiquette for a prince to speak at mealtimes and the habit of silence had become too strong for any of them to break it, even in exile. The etiquette of the Court had been drawn up during the reign of a king who not only did not speak at mealtimes, but spoke hardly ever between them, for the reason that he had nothing whatever to say. The Chancellor, who had governed the Kingdom and amassed an enormous fortune in doing so, established this taciturnity as a Court rule. The rule had been maintained and now the custom that had been designed to cover the ignorance of one king was held to be essential to the dignity of his successors. Since it is as difficult to stop making rules as it is to stop

eating almonds, once having started, the King and the royal family were soon surrounded by so many ceremonies that a theory was necessary to account for it. Several learned Brahmins set to work at it and thus arose the doctrine that monarchy was a divine institution. This was satisfactory and reasonable, since the gods, by definition, are capable of anything. The meal, then, proceeded in silence.

When the lamps were brought in, this silence was broken by the sound of music. The music came from outside the house. Rama looked up from the banana leaf on which were the remains of his meal, and his face showed astonishment and displeasure. This was because the musicians outside were playing the wrong tune for the time of day.

Music, of course, started with people singing and in more barbarous days people had sung when and what they pleased. With the progress of civilisation they had been put in order and the principles of good taste had been established. A celebrated Brahmin analysed all the melodies which he heard people sing and found that there were exactly twenty-four, a number which was later revised by an equally celebrated Brahmin, who found that there were exactly forty-eight. It was found, also, that the commonest cowherd knew all twenty-four (or forty-eight) often as well and sometimes better than the most learned musicologist. Plainly there was a flaw in this, and it was soon brought to light. The first of the celebrated Brahmins found that where the cowherd differed from the Brahmin was that he sang as his vulgar spirit moved him. More cultivated people, however, ought to sing the tune most suitable for the mood of the hour. From this it was only a step—or, better, a happy skip—to drawing up a list of the twenty-four tunes arranged according to the twenty-four hours. (The second Brahmin later arranged the tunes for the half-hours, but agreed with his predecessor in his fundamental principles.)

This settled, the way was clear to make a rule that people of good taste would sing or listen to the prescribed tune at the prescribed hour and to nothing else. This being the most

extravagant absurdity, it followed inevitably that the gods were called upon to support it, which (according to the Brahmins) they did. The gods announced that they were only pleased by certain sorts of music and that all other music offended them. These sorts were listed by the Brahmins. Very soon a literature grew up round the subject and then another literature explaining the first. Among men of taste and fashion it was considered essential to have a nodding acquaintance with this immense compilation of criticism, and the habit of listening to a good tune and enjoying it died out. Instead a musical performance became a desperate business in which both the listeners and performers tried to display their erudition. The resulting music was offensively bad, but since nobody expected to enjoy it, nobody was disappointed. The sounds that Rama now heard were tuneful, happy, and wrong.

At this point a peasant woman came into the room and after saluting Valmiki, she took Sita away to help her prepare for the night. Sita touched her husband's sandals, as good manners prescribed, and left silently, as became a woman. But all this took time and the music outside changed before Rama could protest. This new melody was not one of the forty-eight—a thing which was strictly speaking impossible. Rama said so, as they moved out to sit on the porch of the house to feel the cool air of the evening.

Valmiki said nothing in reply to this, but sat for a while listening to the music. Some of the hermits had gathered under the tree, squatting by the grey columns of the aerial roots and looking towards two of their company who sat with their backs against the bole. One of these two men had a zither with a great number of strings which he plucked rapidly, making a humming music, the melody of which was subtle and long, its shape emerging from the deeper notes and then retreating again, like an iridescent snake glimpsed in long grass. The other man was singing. To follow such a melody demanded prolonged control of the breath, and

this he achieved by moving his hands and arms, expanding and deflating his chest as he did so, but unobtrusively, since he matched his gestures to the meaning of the words, pointing the phrases, and illustrating the meaning in a ceaseless weaving of his bare arms and his brown hands. Behind him the river lay silver in the last short light of the evening, and black canoes, slowed by their paddling crews to catch something of the song, passed behind him and so out of sight round the bend of the river, where Rama could see the paddles rise, drip, and plunge again, in rhythm with the singing. On the river's far bank, the forest was already dark, and fireflies had begun to dance in pyramids above some of the trees.

Then the last light faded from the sky and in a matter of minutes it was quite dark, with the sudden soft darkness of the tropics. The singer and the zither player ended their song, whether because they had reached its end or because of the darkness it was difficult to say, for the melody found no resolution, the last note thinly aspiring like the finial of a tree. A servant walked towards the tree carrying a tray of earthen lamps, which the listeners placed in a semi-circle at the feet of the singers. Rama used this pause to say:

"I am surprised that a poet—an artist—like yourself should not find such music objectionable. I mean, at this time of day—or for that matter, at any time. I don't recognise the tune at all."

Valmiki's boy came on to the porch, carrying a tray with four lit lamps which he placed in brackets on the wall of the hut. Valmiki watched him do this before he answered Rama, and Rama saw by the light of the lamp that Valmiki's face was creased in his disconcerting grin.

"It is strange," thought Rama to himself, "that I, a prince of the blood royal, should sit here in the forest talking about music to a man who has murdered a Brahmin—although it is difficult to imagine him doing it—and who admits to four thousand other crimes. But it is the will of the gods."

Luxmun for his part, thought, "I am glad he's brought the lights. A man can see what he's at if any trouble blows up. There is my spear leaning in the corner, the left-hand corner. Although I must say this fellow seems amiable enough. Still my brother says he is a dangerous man and what my brother says is right."

The boy turned to go, but Valmiki said, "Wait." The boy obeyed, standing in an unembarrassed way, looking at his master. Valmiki said to Rama:

"Have you ever seen the sea?"

"The sea?" said Rama and felt with some resentment that this dubious man had a knack of suddenly making him feel young just when he thought himself most mature. "No. You mean the Great Water? No, I have not seen it. But of course my tutors have fully described it to me. It resembles green glass. It is inhabited by a race of men and women whose lower bodies are fishes' tails, a punishment for their having refused to give a Brahmin the best piece of fish when he was eating with them in some previous life."

The shadows in the lines beside Valmiki's mouth grew deeper.

"I have seen it," he said. "Before I came here I wandered over most of our land and I spent some time among fishermen in a village by the sea. No doubt if the Brahmins say so, then the sea must be inhabited by men with tails. I never saw one. But I saw something which struck me as much more marvellous.

"What was that?" said Rama and Luxmun together.

"Look," said Valmiki, and pointed to the waiting boy. "Do you see what he wears in his ear?"

The boy smiled at the Prince in a manner which would have earned him prison for insolence in Ayoda, and turned his head so that they could see two pieces of curiously shaped pink stone that hung in the lobes of his ears.

II

The Conspiracy Revealed

"THAT stone," said Valmiki, "is made by an insect no bigger than the smallest gnat. It lives in the sea. It builds itself a small crooked house, and other insects build houses on top of it. They go on building, year after year, in shapes more and more fantastic, until they have built a hill. They go on building upon the hill until they have built a cliff. Then they build on the cliff until it rises out of the sea, and the water which once had been smooth—not as smooth perhaps as green glass—but still, smooth, now breaks into white foam that roars continuously against the innumerable pink houses of the little insect.

"I think I remember hearing something of the sort," Rama began, but Luxmun, round-eyed, better expressed his brother's feelings.

"How extraordinary," he said. "A cliff? How long does it take?"

"I have no means of knowing," said Valmiki. "I was not there long enough to see a house built. I went on my travels again and I saw many other things perhaps just as curious. I saw a judge order one man to be fined a silver rupee and another man to be mercilessly flogged, both for the same offence. And what was marvellous was that everybody, including the flogged man, thought it was just. It was the law of the land that a man of darker skin should be punished more severely than a man more pale than he. This, they proved, was bound up with the origins of the world. It is an interesting proof but I shall not repeat it for the first part of the exposition alone takes two hours. Then I went on a journey into the western lands where the men are all pale and of extreme refinement. I found a vast building inhabited by men who had castrated themselves in honour of a goddess

who lived, they said, in a black stone which smelt abominably of the rancid oil which they poured on it every hour of the day and night. They accompanied their worship with hymns which they sang in high cracked voices. In one part of the building was a long room at which twenty men worked at desks continuously inscribing diatribes against men who were physically complete and made use of their advantage in the customary manner. Nobody in the Kingdom could aspire to being considered a learned man unless he was willing to make the same sacrifice as these devotees. One man, who claimed to have invented a method of measuring the area of curved surfaces—I cannot say if he had really done it or not—was refused a hearing on the grounds that he had raised a family of five children and was therefore no scholar. They showed me a catalogue of their writings which already runs to a room full of scrolls. It is not complete and never will be, for dissertations are produced more quickly than they can be listed, since the cataloguers are themselves writing dissertations, on the proper principles of listing dissertations. My mind began to ache after a short sojourn among these people and I passed on to a country which lies beyond the Hindu Kush. There I talked across a small boundary stream to an old man who was voluble in the praises of his native land in which he had not set foot for thirty-seven years. The little stream over which we talked was the boundary of the country. Thirty-seven years before he had gone across it on a journey. While he was away, an enemy laid information against him, and his return was forbidden until the magistrates had decided upon his case. The enemy had said that the absent man had once disagreed when someone had declared in his presence that the King's second daughter was the most beautiful woman in the world. The unfortunate man, through his representatives, denied that he had ever said it, or, if he had, then it was not sufficient ground to separate him from his home, his friends, and such fortune as he might have after paying his legal expenses. The case became celebrated. Each magis-

trate upheld a different opinion and in a few years candidates for the office of justice were required to produce opinions of their own. Meantime the man was ruined, his wife died from vexation at having to live in a hut on a river-bank, and the Princess who had been the cause of the matter at the age of twenty-two became a mature woman. When I saw her she was beak-nosed, rheumy eyed, and had developed a formidable and hairy wart on her right cheek. For all that, the man himself and everybody that I met were immensely proud of the way things had been done. It proved, they all said, how careful their government was to protect the freedom of the subject. The scrolls recording the various opinions were of the finest vellum, tied up with red tassels, and a copy of each one was always sent to the man across the river, who, having heaped them conveniently, sat on them, since he had sold all his furniture to fight his case.

"Now," said Valmiki, "when I returned from my travels in other countries and I settled here to think about them, it seemed to me that I had made one discovery. I had found that clever men greatly resemble the insect that made the earrings in my servant's ear. They will elaborate vast structures of thoughts from their very nature. They cannot stop, even though the thing they are building is senseless. They must go on. And we must live in the nooks and crannies of their aimless building, and sometimes be imprisoned in it, as they work, endlessly, surrounding us, closing our escapes, until we live and die a part of the gigantic folly, as blind and in as deep a darkness as its frantic builders."

While he had been speaking lights had appeared in many of the other huts, while the lamps under the tree where the musicians sat shone more brightly. The sound of talking and laughter came through the still air, with the echo that is not an echo, but an underlining, an enrichment of the sound, that marks the tropical night.

Prince Rama had listened to Valmiki with great attention. He had been thought an admirable student in his

youth; that is to say, he had developed the habit of listening with the appearance of pleasure to long speeches from elderly men, whom he never interrupted. As Valmiki had progressed Rama grew more and more at a loss to discover what he meant, but the less Rama understood the more profound grew his attention. He was therefore caught quite defenceless when Valmiki turned to him at the end of his speech and said:

"So you see that a man with ideas like mine might very well have killed a Brahmin and eaten a hearty meal to top it off."

Rama blushed and the carriage of his handsome head lost a little of its nobility. He had been thinking this very thing.

"Did—did you kill him?" asked Luxmun.

"What would be the use of killing one Brahmin?" asked Valmiki in return.

Luxmun, to Rama's surprise, and not a little to Valmiki's said:

"Yes. I quite see what you mean." He nodded his head sagely and stroked his moustache, a sign that his mind was running on his military career. "When I was just about to engage the King of Magada's forces on the morning of the Battle of Tamralipti I was on the end of the line and we opened the engagement—not that we didn't have to finish it as well, for Raja Bhuma—he was in charge of the elephants—lost his head completely and charged off the field in the wrong direction just when we had them in the hollow of our hands—blaming it *of course* on to the elephants, though I said then and I say now an elephant's toenail knows more about fighting than Bhuma's will ever learn—so he left it to us, as I was saying—what *was* I saying? Oh, yes. In the morning when we were just about to engage I said to myself, 'Suppose I kill one man, or two, or three, or four this morning, what difference will it make to that trampling herd—the enemy I meant. Fright, you see. Pure fright. When they sounded the conch shell, in I went, still frightened out of my wits and then—*clang*—I got my

mace on one of their helmets and down he went, then—*clang*—I got another and then, well, I laid out eight before I got my second wind and that was just the beginning. But that's what I mean you see, you've just got to make a beginning and what I always say is—correct me if I'm wrong—but you begin with number one and let number two, three, four, and so on take care of themselves. It's like that with your Brahmin, or," he said, catching his elder brother's eye, "perhaps it isn't."

"No," said Valmiki, smiling at him, "I am afraid that it isn't. You see, I have not even started with number one."

"Then you did not kill a Brahmin?" said Rama.

"On the contrary," said Valmiki, "I have committed a much worse sin. I have made, I fancy, one or two of them immortal."

The zither player sounded a new melody and this was greeted with murmurs of approval from his small audience. One or two of them could be seen to turn towards Valmiki's house as the zither played. Valmiki said:

"Now, if you are not too tired, I would like you to hear some of my four thousand other crimes. I fear that they must be very good or I would not be sitting here in the middle of the jungle as I am."

Rama, quite mystified, was about to ask him to explain when the singer began the *Song of the Parrot.* It did not tell of the conspiracy in all its details—Valmiki did not know them all till many years later, when he put them in and, later still, the Brahmins cut them out—but it told enough to bring Luxmun to his feet in anger before half the song was done. Sita, hearing the song through the thin walls of the hut, came to a window and listened. She, too, grew angry, especially at that part which told of the pastry cook: for their conversation was an invention of his: she had done no more than thank him and give him money.

As for Rama, he listened unmoving, but, as the narrative drew to its close, he took his gaze away from the singers and looked fixedly at the ground.

When the song was done, he said, in the silence that followed:

"That is a most ingenious invention. I congratulate you."

"I wish it were an invention," said Valmiki. "I would think myself even cleverer than I do."

"Then it's all true?" said Luxmun.

"As far as it goes," Valmiki replied. "Yes, it is true."

"You are very well informed," said Rama, "considering you are an exile."

Valmiki said:

"Very."

Then he called a name and two people came towards the hut from the banyan tree. The other hermits fell silent and watched them. When they came up to the place where Rama was seated, they slowly kneeled and then touched the ground with their foreheads. By the light of the lamps Rama saw that they were the old man and his wife whose son the King his father had killed.

"You know who they are?" said Valmiki.

"Yes."

"Then you must forgive them. They have been very unfortunate and they cannot be blamed. On the night before the King held his audience, they were taken, by his orders, by two torturers and . . ."

Rama got up. For all his simplicity he had the authority of a prince when he chose to show it, as he did now. Valmiki fell silent.

Rama went to the old man and the old woman and raised them gently, saluting each of them, the first in the fashion of a son saluting his father, the second with the reverence of a son greeting his mother.

"You were made to lie?" he asked them.

The old man said, his voice shaking, "They did not hurt us. They showed us their ropes and whips. They showed us the blood on the floor and told us it was from a servant who had just received an hour's punishment for disobeying the

King. We are very old. We were very frightened. My wife vomited. So we lied as we were told."

"Then you never bound the King to a vow?"

The woman said:

"We have never done a cruel thing in our life. I do not know why people are so cruel to us. We forgave the King that night and we were happy when he built a temple. He left us in peace for years until one day we were dragged to his court because he wanted . . ." Her old voice was rising in anger, but her husband bade her be quiet.

"We ran away, when Your Highness left," he said, "and they chased us through the woods and shot arrows. But we escaped and his Reverence here, Valmiki, gave us shelter. We were frightened when we saw you speaking to him, but he sent a message to us in the evening that you were a good man—may Your Highness excuse the phrase—and we were not to be afraid."

Rama stood for a moment quite still. Then he stooped swiftly and lightly touched the feet of first the man and then the woman.

"Forgive me," he said. "I am not a good man. But I think I am a very great fool."

He walked quickly away into the darkness. After a while Luxmun took his spear and followed him, pausing to whisper a word to Sita as she stood at her window.

Valmiki sent the two old people away with a kind good-night. He then sat staring into the darkness until the hermits had gone back to their huts and the singers were asleep. The boy, sleepily looking to the lamps an hour later, saw that he had not moved: and that he was not smiling.

III

The Tale of the Passionate Ascetic and the Hidden Wife

WHEN Rama set out for his night's walk in the surrounding jungle, he had intended to review his life, but he discovered like most young men that he had never taken any notice of it. He had lived happily, but inattentively. He had known that the Court was full of intrigue: he had seen men rise and fall and be destroyed because of it. But he had never considered that intrigue could have anything to do with himself, because he could not imagine anybody disliking him in so marked a fashion.

As he walked he reflected that he had always aimed to win golden opinions from his elders and betters. He leaned against a teak tree and recalled that he had always got them. He sat down and decided that that must have been the cause of the trouble. He rose, very considerably wiser than when he had sat down.

Meanwhile Luxmun from a discreet distance kept a watch for beasts of prey.

Some two hours later he had walked out of the forest into a small plantation. It was three o'clock in the morning and Rama felt deeply sorry for himself. He sat down again and putting his face in his hands, wept for his folly.

Luxmun, in a discreet voice, offered him some mangoes. Rama ate one and sighed. Luxmun peeled another with hi hunting-knife and Rama ate it, absentmindedly. Luxmun peeled yet another intending to eat it himself, but Rama took it, thanked him, and consumed it. They ate about a dozen and the moon rose. Rama attempted to resume the thread of his melancholy thoughts, but Luxmun was cracking the great mango pips to find if they had beetles in them. This is an idle Indian pastime, the interest lying in the fact

that the weevil is found only in a small proportion of the fruit (which it enters in the blossom stage) and one can lay bets. Rama laid bets, won, and felt much inspirited.

However, when the first light of morning began to turn the river pale, he reminded himself that the new day would be very different from those that had gone before. He had been stripped of many illusions and one of them was that he had cut a fine figure by going into exile.

When the sun was just about to rise Rama looked at the world of men and found it distasteful. He walked somewhat apart from Luxmun and after a while he came to his decision.

He would finally renounce the world, and as a mark of his new-found maturity, he would ask Valmiki, the heretical exile and despiser of Brahmins, to invest him with the saffron robe. Thus, he felt, he would regain his self-respect and the respect of the world which (he reminded himself) was nevertheless a despicable one.

He said to Luxmun:

"Let us go back."

He woke Sita, who was dozing fitfully beside the window. He said:

"Where is the hermit's robe?"

She dutifully repressed her joy at seeing him return safe and sound, and stifling a yawn said:

"In the bundle."

She produced it and a few minutes later she and Luxmun heard with utter dismay that Rama was going to send them back to Ayoda.

In the hour that remained before Rama fell asleep from weariness, he explained to them that chastity was the first requisite of the true renouncer of the world. In this matter he would brook no argument, but quoted, in a melodious voice, several stanzas of a celebrated work on self-restraint and its spiritual joys. He felt, and looked, very much his old self.

He told his wife that although she disliked leaving him

now, she would not later on, when she came to reflect on the austerities he would practise and how difficult they would have made her life with him. The indignant Luxmun he tried to soothe by explaining that someone would have to take Sita back to civilisation. That done, he did not object to Luxmun returning, but he thought the life not one for a soldier.

Then, overcome, he lay on Sita's bed and fell into a dreamless sleep.

Valmiki was looking sadly at his meagre pumpkins, a thing he did on rising every morning, when Luxmun and Sita climbed on to his terrace and saluted him. He showed them his garden and listened to their story. Sita felt that he was more interested in his seedlings than her troubles, and in competition with them, spoke out more than she had ever dared in her life.

When, in the still hour that follows eleven o'clock, Rama came to Valmiki with his hermit's robe on his arm and without his hunter's quiver, he found the poet sitting on the root of a carob tree. Valmiki invited Rama to sit beside him and directed his attention to the magnificence of the view that lay spread out at their feet. Rama looked at the river, the forest, and the peaceful hermitage and said, to open the conversation which Valmiki was giving him no opportunity to begin:

"For myself I shall choose a hermitage which is more austere."

"Which would you prefer," said Valmiki, "the desert? That is extremely trying, I believe. Or perhaps snow and ice?"

"Snow and ice," said Rama sharply, because he had seen the smile deepen on Valmiki's face.

"A good choice. They are very cooling to the fleshly passions, I am told." And here he began to quote verses from the poem in praise of chastity that Rama had recited the night before.

"I greatly admire the author of those verses," said Rama, and he shook out the folds of his gown and cleared his throat.

"His real name was Kumar," said Valmiki, "I suppose that you never knew him. No, you would have been too young. But if you like—and there is nothing else to do at this hour which is very inauspicious for beginning any important action—I will tell you about him."

"Do," said Rama, "I shall be glad to hear anything about so virtuous a man." So, moving his seat a little so as to be in the shade of the thickest branch of the carob tree, Valmiki began:

In his prime (said Valmiki) as a preacher, Kumar was the best known spell-binder north of the Vindhya mountains. He travelled the whole country calling upon the population to renounce the vanities of this life and to live in holy simplicity. Kumar himself was not very holy and he was the reverse of simple. But he did sincerely think that a life of renunciation would be better for everybody, including himself: and, to do credit to his honesty, he never said that a life of self-denial was easy.

Most hermits live hard lives in their hermitages and taste the flesh-pots of the world only when they come out of them. Kumar reversed this. He lived rather comfortably in his hermitage, where nobody saw him, and he lived with gaunt austerity in places where he was more under observation. By this means he managed to be publicly edifying and personally sound in wind and limb. If his tall, half-naked figure showed rather fewer bones than it ought, it did not matter. His fascination lay in his eyes which were large, black, and always burning.

It was these eyes which won him his principal admirer. This was Govinda, by far the richest cloth merchant of Ayoda, who had in the way of wealth and terrestrial comforts more to renounce than any other member of his caste. He had grown in girth and weight step by step with his business; by the time he met Kumar his warehouse and his cummerbund were the most impressive sights in Ayoda after the royal palace and the main temple.

Hearing Kumar preach one day on the temple steps (for the Brahmins would not allow him to preach inside) the cloth merchant was converted the moment that Kumar ran his burning eyes first over Govinda's belly and then over his face. He asked Kumar to take a meal with him and when Kumar had eaten it he told the ascetic that he had made up his mind to give all his worldly wealth to the poor and to join Kumar in his hermitage.

Kumar surveyed the remains of the sumptuous meal with his burning eyes, dabbled his fingers in a silver bowl of rosewater, and picked his teeth with a jewelled toothpick that had a most amusing little set of miniature gold bells attached to it so that it tinkled as it was used. Kumar produced a lengthy tinkling before he answered.

Then he said this:

"Good. God be praised. Honour and glory to Shiva, lord of ascetics for another saved soul. But, my friend, I must warn you that the path is far from easy."

"No, I don't suppose that it is," said Govinda, "but I am used to doing difficult things. Still, I suppose it will at least be easier to give away my fortune to my poorer neighbours than it was to make it."

Kumar thought of all the good things around him disappearing, as, so to speak, he set them to his lips, like a fairy feast. His heart jumped, his palate went dry, and he took a long draught of sherbert from a bronze cup with silver inlay work. He thought quickly. He looked at his host over the brim of the cup. The men who lead us upward to higher things share one gift with those who lead us downward. They are good judges of character.

"There are harder things to give up than money," he said.

"Name them, master."

"For one," said Kumar. "Women."

"At my age," said Govinda, "such pleasures are not important."

Kumar shook his head.

"Nobody can make that remark truthfully," he said in his best oracular manner, "over the age of fourteen."

Govinda smiled.

"I don't deny that it has had its attractions for me," he said. He gave a reminiscent belch. "But with your example in front of me, I shall rise above it."

Kumar politely echoed his host's belch. Kumar's belch was non-committal.

"You are married, of course?" he asked.

Govinda clapped his hands. He was a very respectable merchant and in his circle wives did not eat with their husbands, but stayed in the kitchen or near it to supervise the dishes. He instructed a bowing servant to call his wife into his presence.

She came. She was swathed in a sari of lustrous Chinese silk tinted with a soft Phœnician dye. It was bordered six inches deep with a pattern of gold thread and the wing-cases of iridescent beetles. She held the head-fold of her sari closely across her face and kept her head bowed and her feet together as she stood before her husband. She was the very picture of a good wife of a substantial merchant.

Kumar greeted her. She did not reply until her husband said:

"This is a learned holy man who is a master of wisdom. His name is Kumar. May it be always pronounced with reverence in this household. You may show your face."

She did, and the master of wisdom instantly succumbed to her charms.

"For a long time," said Govinda, to his wife, "I have thought that life held something bigger and finer than selling pieces of cloth. Master Kumar has shown me that it is. Do you understand?"

His wife lowered her eyelids respectfully. She inclined her head obediently. She parted her classical full lips to show her perfect teeth.

"No," she said.

"It is difficult to explain to a woman," said Govinda.

.:vertheless we should try," said Kumar. "Women
"Ngh a grave temptation, are God's creatures." And
althoughanked God in his heart that He had made this one.
Kumar t.," he went on, "that I shall experience a sudden
"It maybeagainst everything human and stay in my her-
revulsion: some ten years or so. I feel that it might happen.
mitage frdoes not, and I come again to Ayoda, I should
But if itit my duty to instruct your wife in the principles of
considerng."
holy livso," said Govinda, "and I shall be doubly in your
"Dcover your face and go." This last was to his wife.
debt overed her face slowly, her features disappearing one
Sh one, each indelibly printed on Kumar's memory. She
bowed deeply to her husband, revealing the magnificence of her haunches, and she left.

For Govinda to have mentioned his wife again would have been impolite and for Kumar it would have been incautious. It was taken for granted between the two men that Govinda's wife would do as he wanted, and the conversation turned back to the path of reunciation and its pitfalls. When at last they rose, and bid each other goodnight (for Kumar had agreed to sleep under Govinda's roof instead of under the open sky as he would have preferred—he said—to do) Kumar delivered a final argument against any hasty action on Govinda's part.

"Now you said that you intend to give away your money."

"I did," said Govinda.

"To the local poor, I understand," said Kumar.

"With your approval," said Govinda.

"Of course it has my approval," said Kumar impatiently, "of course, of course, of course. It is naturally pleasing to the gods that you should give to the poor. You will earn merit."

"So I had hoped," said Govinda and since they had reached the guest chamber, he added, "There are four lamb-skin rugs from Bokhara on the bed and two quilts of swans-down. You will want these removed, of course, master?"

"Don't trouble," said Kumar. "If I sleep at all, I shall sleep on the floor. You may leave them in place."

"As you wish, master."

"As I was saying," resumed Kumar, as the two men held hands in wishing each other goodnight, "to give to the poor will gain you merit. Now it follows that to give more to the poor will gain you more merit. It follows, again, that if you delay your action, as I advise, on spiritual grounds, you will go on making more money in the meanwhile, and so you will have more to give away when the time comes. More haste, less merit. Does my reasoning satisfy you?"

"Eminently, master," said Govinda. Both men at that moment breaking into a simultaneous yawn, they parted. Kumar, having ascertained that it would be a moment's work in the morning to put the coverlets straight, flung himself down on the Bokhara's and dreamed of his host's wife.

Kumar returned to his hermitage the next day, greatly impressing Govinda with his self-abnegation. His disgust with humanity lasted seventy-two hours and to Govinda's great delight, he once more appeared in Ayoda, preached, and was borne off to Govinda's house. When they had finished an even more sumptuous meal than the first and when it was done and both men were tinkling their toothpicks in the most companionable manner, Govinda said Kumar had been away much too long. Kumar heartily agreed but prudently refrained from saying so. Govinda complained that without Kumar's elevating conversation daily life was a grey monotony. If at the end of the day he had accumulated twenty pieces of gold ("Twenty?" said Kumar. "I don't mean market days," said Govinda), well, what were twenty pieces of gold? Twenty was a small number compared with the Infinite; and gold did not shine so bright as the hermit's begging bowl.

With these sentiments Kumar sagely agreed since they had been copied word for word from his morning's sermon.

He waited for Govinda to come to the point. He was well satisfied when Govinda did.

"You mentioned that one of the difficulties in the way of renunciation was women," said Govinda, "and you were, as inevitably you must be, right. My wife will not hear of the idea."

"Let me talk to her," said Kumar more quickly than he could have wished. A new brilliance came into his already burning eyes. Govinda noticed it with awe.

"I see that you anticipated my wife's stupidity," said Govinda. Kumar anticipated a good deal more, but he nodded his head.

"I saw when I first met her, that she needs instruction. Lengthy instruction, I am afraid. She has not got your own quick grasp of sublime truths."

"For that reason," said Govinda, smoothly accepting the compliment, "I had hoped that you would honour my house by making it your home for the rest of the hot weather season. I fear for your health in that remote spot where you live, especially when the sand-wind is blowing. Thus if you condescend, we shall kill two birds with one stone."

Kumar accepted, and privately determined to kill three.

Govinda's wife received him at their first interview on the verandah of the women's quarters. But the heat increasing daily, Kumar suggested that they continued their instruction inside. Once inside he was able to get closer to both his theme and his pupil. His passions rose higher with every meeting, but if he had lost his heart, he kept his head. He realised that he had to do with a faithful, if not very loving, wife. He decided that it would be impossible to seduce her under his host's roof. He therefore put her under a vow of secrecy not to reveal to her husband what he was about to tell her, and this settled, he proceeded in the following manner:

"I have just explained, my dear, the ksana-bhangarada doctrine, which as you know says that nothing lasts longer than an instant. That, I suppose, is just about the time that my explanation stayed in your pretty head."

Govinda's wife lowered her darkened eyelids, parted her classically full lips, showed her faultless teeth and said:

"Yes."

"Very well," said Kumar, "now I will tell you something which will not be beyond your powers of understanding. But you must promise never to mention it to your husband. Do you promise?"

Govinda's wife nodded. The jewelled plaque which she wore on her forehead bounced in a way which Kumar found alluring.

"Your husband," he said, "is not really going to renounce anything. He is going to give his money to some trustworthy neighbours. Then he is going to desert you, dress as a hermit, and then he is going to Benares to live with another woman. Once everything has settled down his neighbours are going to take the money to him and in return for a consideration, give it back to him. He has told me that he cannot bear the sight of your face another moment. This other woman," said Kumar relentlessly, "is a Kashmiri whose complexion is like that of the tusk of an elephant reflecting the rosy dawn."

The part of this total lie which pleased Kumar best, as he thought over it in the next few days, was the Kashmiri woman with the good complexion. The business of the tusk and the dawn, showed, he thought, a capacity for poetry in him which had been buried in the course of his practice as a rhetorician. Had he not had the wife of Govinda to love in the flesh, he would have been enamoured, he thought, of his own fiction.

Next, he admired the artistic flourish of asking Govinda's wife not to tell her husband. It was pure ornament. He knew quite well that she would tell him and he had already prepared his defences. This he had done quite simply by telling Govinda that his wife had conceived the silly notion that her husband's renunciation was a mere deceit to enable him to live with another woman in Benares. Govinda

laughed heartily when he heard this story the first time (from Kumar) and even more heartily when he heard it the second, from his wife.

Kumar quickly pointed out to Govinda's wife that this was exactly what her husband might be expected to do. She put her face in her hands and cried. Her ornament bobbed more alluringly than ever.

Kumar's plans went well. Each time Govinda's wife spoke to her husband he declared that the day of his great renunciation was nearer. The actual moment awaited the decision of Kumar, who, Govinda told her, was a man she should listen to, respect and obey. Each time Govinda's wife spoke to Kumar he drew a more detailed picture of the illicit household that was to be set up in Benares, and a more gloomy picture of the fate of Govinda's wife, deserted, despised, a widow without the chance to gain *éclat* by committing suttee. He also enlarged upon the charms of living in a hermitage: first, in any hermitage; later, in his own.

One night he came to the women's quarters in a feigned state of agitation and told her that she must decide. Her husband was pressing him to name the day of the renunciation and he could not delay any longer. If he refused to give a propitious time, Govinda would choose his own, and they would gain nothing. There was no alternative. Either she fled with him instantly (for he had already warned Govinda that he might leave for his hermitage to meditate his decision) and kept her self-respect, or she would be deserted and soon—when the true story was revealed by gossiping neighbours—disgraced.

She fled with him.

IV

The Tale of the Hidden Wife continued

FOR the first few days at the hermitage, Kumar set his beautiful disciple a strict regimen of prayer, meditation and the saying of hymns from the *Rig-Veda.* She obeyed enthusiastically, but this did not worry him. He had begun in the same way when he had set up his hermitage and he knew she would soon tire of it. So she did, after a very few days, and Kumar rejoiced. He had restrained himself as a lover with a fortitude which he had never shown as a saint. He was glad that the trial was over, save for certain steps which he had had in mind from the very beginning.

Catching her yawning one day, he said:

"Are you thinking of your husband?"

She screwed up her pretty eyes and set her classic lips.

"No," she said, between her flawless teeth, for she was still extremely angry whenever his name was mentioned.

The next day, catching her yawning again while she was saying some prayers, he said:

"You have acquired great merit. You have renounced the world and you have renounced your husband. You are living a holy and chaste life. But you can acquire still more merit. Do you know how?"

She opened her correctly curved lips in a vaster yawn than ever and said:

"No."

"By renouncing the renunciation," said Kumar. "That is the path of ultimate perfection: that is the way of uttermost detachment. Now you are bound. By what are you bound? Do not trouble to answer yourself: I will do it for you. You are bound by your desire to live a life of renunciation. This is called spiritual pride. Do you understand? It

does not matter if you do not. The next point in my argument is the important one. To gain the ultimate merit of renouncing the renunciation, you should do something which shows that you have a contempt for your own endeavour to be holy. For instance, you could renounce chastity. Or," he proceeded with a show of open-mindedness, "any other austerity that you would prefer to renounce. Is there," he said, taking her hand and gazing at her with his burning eyes, "any other?"

She lowered her eyelids, now innocent of paint but not less beautiful. She pursed her mouth and looked between her lashes at Kumar's frame which was somewhat too sturdy for that of a holy man.

"No," she said.

They retired to an inner room of the hermitage. Kumar undressing, recited several verses of great beauty in praise of chastity. He added some of his own, extempore, which announced that this virtue was about to be abandoned by two devotees who wished to show their humility. With that he proceeded instantly to embrace her. The versified prelude to their enjoyment proved no worse than any of the other devices of lovers. The sacrifice, on both their parts, was wholehearted. At Kumar's suggestion to gain further merit and to make their humility beyond doubt, they repeated it.

At Kumar's suggestion, again, they sacrificed the following afternoon and at Govinda's wife's prompting they observed the ritual again at night. Kumar was a man beside himself with joy.

In this mood he readily agreed to go to Ayoda and gather news of what had happened. Since he had already settled in his mind what the news should be, he went with a light heart and, as was his custom, an ingenious lie ready on his lips.

He found Govinda in his warehouse. Govinda hastened to greet him, but seemed in no hurry to mention his wife.

"You must forgive me for welcoming you here," he said, bowing deeply, "but a new parcel has arrived from China,

of the most wonderful silks. I am disposing of them at a handsome price—in accordance with your wishes, of course, master. Have you," he said, and Kumar detected some hesitation in his manner, "settled on the propitious date for my taking up a holy life—beginning it, that is, of course. I do not suppose that the thing can be done in a day."

"Govinda," said Kumar with his most solemn voice, "I am the bringer of bad news."

"There is no propitious date?" said Govinda, running his eyes over his tight-packed shelves. "Well, well. One must be resigned to the will of the gods."

"Your wife," said Kumar, "is dead."

As Kumar had planned it, the rest of this lie was as tremendous as the beginning. But his plan went wrong and the best parts of the grand lie were never told. Kumar became quickly aware that Govinda was barely interested.

"Dead?" said Govinda. "May she avoid the noose of Yama," he said, a pious expression which meant that he hoped she would not be dragged down to the god of Death's grey hell. "She ran away from me, you know." He flicked a bead of the abacus in front of him. "Or perhaps you do not know."

"I had heard," said Kumar, with circumspection.

"She ran away on the night that you went back to your heritage. She made fine fools of us both," he said. "Or perhaps it would be more respectful to say that at least she made a fool of me." Govinda flicked several beads along their wires with deliberation. "All the time that she was accusing me of having a plan to run off to another woman, she was planning to run off to another man."

"How do you know she ran off to another man?" said Kumar.

"She was seen in the company of one at the town gates. The guard couldn't swear to the description of the man. He bribed them, I suppose. Well, now, dead, you say?"

"Alas, yes," said Kumar. "Her body was found by the holy bathing *ghat* in the Mother River near the place where it leaves this Kingdom. The Brahmins there gave her the proper burning ceremony for a wife. I happened to be passing there, and they told me of it. They had this. I recognised it."

He held out the forehead ornament. Tears came to his eyes, partly by plan, but partly through the strain of searching Govinda's face for some clue to what he was really thinking, Govinda gave the ornament a casual glance.

"Make a present of it to the—Brahmins for their—trouble," he said, pausing between his words and emphasising some by a flick of his beads.

"You take your wife's death calmly," said Kumar.

"What is death but a blessed release?" he said, in the formal phrase. "Of course you will dine with me?"

Kumar accepted. The food was delectable but the banquet was not a success. They discussed philosophy, but languidly. Govinda went back to work during the night in his warehouse. He was affable: he was even happy; but Kumar could not make him out. Kumar left next morning for his hermitage. Govinda bade him a warm farewell; Govinda pressed him to come again; Govinda went off to his warehouse humming a tune; but for all that, Govinda remained a mystery.

Govinda's wife bit her classic lips with rage when Kumar, on his return to the hermitage (a day and a half's rough journey from Ayoda) broke the news to her that her husband had fled to Benares. She went for a long and angry walk in the surrounding forest, but the forest being thick, the weather hot and the hermitage being not without its attractions, she returned in a good temper and suggested to Kumar that they once more renounce the renunciation.

Kumar was weary from his journey and would have preferred a bite to eat and a good sound sleep. But Govinda's wife was determined and for that reason more alluring than

ever. They embraced several times with all the passion aroused by absence.

They embraced on the next day, at the suggestion each time of Govinda's wife, this time with all the ardour of propinquity.

They embraced on thirty succeeding days, and, so far as Kumar was concerned, on the thirtieth with no ardour at all.

Kumar wearily asked her, on the thirty-first day whether she did not think that they had piled up sufficient proof that they had no spiritual pride in renunciation.

Govinda's wife set her impeccable lips, looked at Kumar through her curling eyelashes and said:

"No."

She went further, which was most unusual for her. She said:

"As I see it we have to show that we can take it or that we can leave it: is that right?"

"Allowing for your limited choice of words, yes," said Kumar, holding his aching head.

"Then we must show that we can leave it."

"We must," agreed Kumar.

"But we can't do that unless we take it," said Govinda's wife. "Is that right?"

"Allowing for your limited . . ." said Kumar, wearily. "Oh, but never mind, never mind," he finished and allowed his head to sink dispiritedly on his chest.

"Good," said Govinda's wife, and placing her arms round his neck she kissed him again and again with her irreproachable lips.

Months passed away in this fashion, and if Kumar found his hermit's life monotonous, Govinda's wife did not. The nearest village was two miles away, but her fame as a holy woman soon reached there. The villagers flocked to kiss the feet of the beautiful hermitess and to have the privilege of speaking to her. Their language was simple and so was hers: their interests were limited but scarcely more so than those

of Govinda's wife. She enjoyed their company and rei
her prestige.

As for Kumar, his eyes no longer burned. On the occasion when he resumed his preaching, at an obsc town some twenty miles away, his lacklustre glance, his e ervated gestures and the fact that he yawned in the midc of his sentence caused him to be chased down the street l the boys of the town as an impostor. He did not expo himself to further indignities. He many times determine to go privately to Ayoda but never summoned up the energ to face the long walk there and back. He spent his tim composing a moral poem on the virtues of chastity by whic he hoped the wreck of his ambitions as a preacher might be redeemed. He threw great feeling into the verses.

Now one of the last vestiges of Kumar's old professio which he had retained was the blessing of the spring caravans. These set out from all over the country at the end o the cold weather to make the crossing of the snow moun tains far to the north. Their road passed within an hour's gentle walk of the hermitage. In common with many othe holy men on the long route to the passes, Kumar would sit by the side of the road in springtime, seated on a mat, his beads round his neck, his forehead painted with the vermilion signs of his calling and read a devotional book. His begging bowl would be in front of him in a conspicuous position. The caravan's master would see him and stop for his blessing, if the owner were devout: and he usually was, for even the most hard-hearted man's thoughts turn to religion when facing the high passes of the northern barrier.

Two years or so from the day he had brought Govinda's wife to his hermitage, he was thus seated by the road-side, nodding and yawning over his book, when a caravan of exceptional magnificence began to approach him along the road.

First came a party of mounted soldiers with bows and swords, shouting and running little races on their squat

er ɔrses, cursing, laughing, clanking their armour, and every o, often taking swigs from leathern bottles which hung from their saddle bows. Their drunkenness proclaimed the generosity and wealth of the owner of the caravan. Next came a long string of camels, loaded high, so that the camel drivers were forced to walk beside their complaining beasts, instead of riding, and constantly to adjust the ropes whose knots joined in the protest of the animals. After some fifty camels all weighed down with merchandise came a company of mounted servants, gorgeously arrayed, and most with soft leather riding boots from Tibet, richly embroidered and all wearing a sash of vermilion silk, the same colour as that which streamed from the lance of the horseman who rode immediately before their master's palanquin.

This was ingeniously slung between two white dromedaries, on the necks of which were seated camel-boys in dresses of fine cotton and small tight turbans with an ornamenting of silver. They guided the dromedaries skilfully, making sure that the palanquin, a box of painted bamboo, swayed as little as the road would allow.

The palanquin had silk curtains, and these, when the palanquin was exactly opposite Kumar, were sharply drawn back. The hand of the owner emerged, and with a snapping of thumb and finger, the palanquin was brought to a halt. Shouts were relayed to the horsemen in front who reined in their mounts and swigged deeply again from their bottles as the dust clouds settled on the halted column.

The owner clapped his hands, the dromedaries groaned and knelt down. The owner got out of the palanquin. He came towards Kumar and bowing in the customary manner asked through the folds of his dust cloak for a blessing. "We go, master," he said, "to China for silk. Pray for our safe return."

Kumar raised his hand in benediction and the traveller piously unwrapped his cloak to bare his head.

"Govinda!" said Kumar, trembling with excitement.

"That is my name," said the traveller.

"And me—don't you recognise me?" said Kumar.

Govinda surveyed him carefully. Govinda's eyes lit. Govinda smiled, and his smile grew broader and broader.

"Kumar," he said at last. "How the—austerity—of your life has changed you. Why did you never come to see me since the day you brought me news of my wife's death?" Govinda shook his head in gentle reproach while his smile stretched, it seemed, from ear-ring to ear-ring.

Kumar summoned his last remaining energy. He was determined, cost what shame it may, to tell Govinda the truth and make him take back his insatiable wife.

"I have to tell you . . ." he began, but Govinda interrupted him.

"You have to tell me gems of priceless wisdom, I do not doubt. Can I ever forget how you laid your holy finger on my trouble at our very first meeting. I was so desperate that I contemplated giving up the world and all my possessions," he said, indicating the caravan with ringed fingers. "All this," he said, "or to be more precise, one-half of this, since I have more than doubled my fortune since I have been able to put my whole mind to it. But you said that it would not be easy . . ."

"Yes, but . . ." said Kumar, and Govinda bore him down.

"And it was not. 'Women' you said were my trouble and you were right in every way except the number of your noun. My trouble was singular, not plural, and from the day you spoke to me I determined to rid myself of her."

"Your wife . . ." shouted Kumar, but his voice was not very loud.

"Had many good points you would say," said Govinda. "That is of course very proper for a man with your charitable view of human beings. But the trouble between us was a matter between husband and wife, something," he said, and snorted as though with suppressed laughter, "I would blush to even whisper in your sanctified ears. But she left me and she is dead. From the day that I was free from her how fully I understood your sermon on the dangers of

fleshly ties binding us to mundane things. Renunciation! That is the sublime doctrine." With this he wrapped his cloak about him, and flinging a chamois bag of money into Kumar's begging bowl, returned to his palanquin, clapped his hands, and was on his way in a great cloud of dust, shouts, cracking of whips and bellowing of camels.

"Your wife is alive!" screamed Kumar, but no-one heard him.

He was not to be defeated. He knew that the road made a great curve to avoid the forest in which his hermitage stood and that the caravan would have to climb uphill for some of the way.

Compelling his tottering legs to break into a run, he set off for his hermitage. He stumbled as he ran and his breath hurt at each beat of his lungs. But despair drove him to do wonders and he reached the hermitage without collapsing.

Yet his appearance was so ghastly that when he seized the wrist of Govinda's wife and glared at her with eyes which now burned as they had done in the days of his preaching, she dared not resist him, but hearing his order, 'Come, woman. Come with me!' she obeyed. As Kumar dragged her along the forest paths, she once or twice tried to find out what had happened. But Kumar had neither the wish nor the breath to reply. Thus running, panting, and tripping over the roots of the trees, they arrived at last at the road as the camels with their high bales were passing by.

The palanquin drew level with Kumar. Frantically waving his free arm (for he kept tight hold of Govinda's wife) Kumar shouted to Govinda to stop.

Govinda's hand emerged from the curtain of the palanquin. Govinda's fingers snapped, and the palanquin halted. Kumar dragged Govinda's wife towards it.

Govinda put out his head.

"Look," said Kumar, his voice cracking with triumph. "Your wife!"

Govinda looked at his wife for a long moment while she,

setting her classic lips, muttered, "Elephant's tusk!" and searched with her lustrous eyes the interior of the palanquin to detect her husband's concubine.

At last Govinda turned his face to Kumar, and with an expression of profound admiration said:

"What power lies in true holiness! You are able to bring back the dead. She is, I know, a phantom, held in her corporeal state for a brief moment by the power of your holy incantations, but how real she looks. How very real." And flinging yet a second bag of money at Kumar's feet he cried to Kumar, "Thank you a thousand times for this lesson in the power of virtue," and to the boys on the dromedaries, "Forward as fast as you can go." The boys shouted, whips cracked, the dromedaries bellowed, the horsemen shouted oaths, and the caravan moved on. When it had passed, Kumar and Govinda's wife were covered in white dust, through which, on Kumar's cheeks, his tears were making dark channels.

His release from this chain of the flesh (which as you know, said Valmiki, is metaphysically known as *moksha*) came six years later when Govinda's wife caught a fever and died. Kumar, once he had seen her well and truly burned to a cinder, flung himself into the work of completing his poem in praise of chastity. He made it a masterpiece. He himself gained a second fame, this time as an author of a morally improving work, until by the time of his holy death he was known throughout the land as the apostle of self-restraint; which shows (Valmiki ended) that the springs of Virtue lie very deep, and sometimes lie in unexpected places.

V

Discoveries

By one o'clock that day the saffron robe was back in Sita's bundle, but this can be attributed only in a small part to Valmiki's story. The tale disturbed Rama and retiring to the cool of Sita's room, Rama had a vision which at first he thought might be a heavenly admonition, but which he finally agreed was sunstroke.

Sita immediately put Rama to bed and the hermit's robe safely away. Luxmun returned hurriedly to the plantation and asked the owner for a basket of mangoes, which, most readily given, he squeezed into a brass jar and gave the juice to his brother to drink. Sita laid wet cloths over her husband's forehead and Valmiki, bustling about his hermitage to prepare light food and restoratives, blamed himself for not warning his guest to avoid sitting in the sun. Sunstroke is rarely a prolonged illness but with a determined wife, an attentive brother, and a co-operative host it can be spun out considerably. Rama was kept on his couch a week, during which he was forbidden to think about his spiritual condition. This prescription, together with a decoction of senna pods grown in Valmiki's garden, soon put roses in Rama's cheeks.

This mild illness was the first he had experienced since childhood and like many other young men who have been tenderly cared for while unwell, he fell in love with his nurse. It did not matter that his nurse was Sita, his wife. He had never been in love with her before because their marriage had been, of course, arranged by their respective fathers. It is one of the advantages of an arranged marriage that it sometimes provides both parties, after years of living together, with that most gratifying of pleasures, a honeymoon without embarrassment. Rama and Sita were young

and they had discovered that they were lovers. They were very happy.

This led to a second discovery. One day while Rama and Sita were strolling on Valmiki's terraces they came across the poet and his servant boy spreading dung on the ground. Rama recoiled from the sight and smell of this and walked away, Sita, following, said:

"But I suppose those vegetables he serves us wouldn't grow if he didn't and they are certainly very good vegetables, especially as they don't cost us a single copper-piece. Of course, Valmiki must be proud to have two princes to stay with him."

That evening, over their meal together, Rama said to Valmiki:

"I have been turning the matter over in my mind and it seems to me that for some months I have been living on other people's charity. When I left Ayoda my mind was too full of other things to think about money."

"Of course it was," said Luxmun, "but my mind's nearly always empty except when I'm fighting so I brought along a little money myself. Still, that's all gone. But you were talking, brother. I am sorry I interrupted."

"Well," said Rama, "I think it would be for the best if I sent you, brother, to Ayoda, to announce that since I am fully determined to stay away from the city until my father's pledge is redeemed, the Royal Council should send me some money for my expenses. What do you think, Valmiki? Is it a good plan?"

"No," said Valmiki. "You should send Luxmun with the message that you are instantly returning. The Royal Council will pay you a great deal more to make you promise to stay away."

"But," said Rama, "I mean to stay away in any case."

"Then you can make the promise with a clear conscience, since you are sure to keep it, which is more than many people can say when they enter into a bargain."

The wisdom of this course being plain, Luxmun was sent

on his errand. He returned a month later with a mule whose packsacks were heavy with gold.

Rama found it difficult to think of a graceful way of paying Valmiki for his hospitality, but Valmiki, being a man of genius and a writer, made it easy for him.

"I would not think of taking money for myself, but if you care to hire two gardeners for a year or so to cultivate my terraces, I shall be grateful," he said.

"I shall be pleased to do that," Rama replied. "I had thought of it myself but I was afraid you would not approve. I remember you saying one day that cultivating the soil was the one truly satisfactory occupation."

"I did," said Valmiki, smiling. "I still do. To make two ears grow where one grew before is a profound solace to my spirit. To watch a hired man do it would be an even profounder solace. I shall be able to devote more time to my poetry."

The matter thus settled, Valmiki asked Rama what he intended to do in the future. "You would be very welcome if you decided to stay in our hermitage," he said.

"The Gluttons are very courteous people," said Rama, "but I have never quite understood their principles."

"They have only one," Valmiki told him, "and that is to eat. They can prove to you by exquisite metaphysical arguments that everything else is an illusion."

"I suppose they eat a lot?"

"Theoretically, they should," said Valmiki, "but people who can draw fine metaphysical distinctions rarely have enormous appetites. I was drawn to their company because I had heard that they spent more time eating than in arguing. If all profound thinkers did that how tranquil the world would be! Alas, my fellow hermits are no better than other men: they all put the world to rights after supper."

"Still, I should find that very interesting," said Rama. "I have thought things over carefully and it seems to me that it was wrong of me to try to renounce the world on the

recommendation of a few self-seeking Brahmins. The proper thing for an intelligent person to do is to improve his mind. I cannot help feeling that what I have lacked is a proper education. I do not—for instance—know anything about philosophy. But I should like to. After all, what can be better for a man than to study all the great thinkers that have gone before us? What could be more fitting than to learn all that the great sages have given to the world? Is there not an eight-fold path to salvation? There is, but I do not even know the names of two of the paths much less all eight. And yet, is there anything more important than the salvation of my soul? No. How can I learn how to save it? By studying the treasures of esoteric knowledge of my forefathers. So I have decided to ask you if you will permit me to stay here with my brother and wife a little longer, and—although I hesitate to take up your time—to put me on the path to salvation."

"By all means stay," said Valmiki, "and you will not take up a great deal of my time."

"How many lessons do you think will be necessary?" asked Rama.

"One," said Valmiki. "Let us begin it under the carob tree at half-past nine tomorrow morning. But this time be careful to sit in the shade."

Next morning, when they had again admired the view from the carob tree and selected each a comfortable root, Valmiki began (and ended) his instructions by telling Rama the tale of the Sage, the Cow, and the Studious Locust.

VI

The Tale of the Sage, the Cow, and the Studious Locust

THERE once (said Valmiki) was a locust who was born in a desert in Baluchistan. On the same day ten million other locusts were born, all of them with identical eyes, identical wings, identical legs and the same thought in their very small brains which was: "I want something to eat."

This locust, however, was different. He had, it is true the same large eyes as the other locusts, the same wings, the same slender legs and his brain was no bigger nor his appetite smaller. He had, on the other hand, a touch of refinement.

When, one day, all the other locusts rose joyfully into the air to go to their first eating ground, he rose with them, but instead of making straight for the food like ten million others, he hung back a little. When the swarm hovered over a blossoming orchard and all the others clashed their jaws in joyous expectation, he looked down and said:

"How beautiful! The blossom is like . . ." But what the blossom was like he never discovered. While he searched for the right words, all the blossom disappeared down the gullets of the other locusts. Sighing, he chose a leaf, and began to eat. As he munched, he savoured its sweet taste. Once or twice he cast hard looks at a locust in front of him who disturbed his pleasure by rending and bolting its food like one possessed. Hard looks having no effect, he tried another tactic:

"How delicious this leaf is," he said to his companion. "I think it must have been specially favoured by the morning sun. Try some."

The other locust stared for a moment at him with protuberant eyes. Then it said: "Eh?" The sensitive locust repeated his statement, in a pained voice with clear enunciation. But his companion was seized with a violent attack of hiccoughs and did not hear a word. It therefore asked "Eh?" once again.

"I said try some of this leaf," the locust repeated, sharply.

"Oh," said the other, and did. In a moment there was nothing of the leaf remaining, except a small square in which the sensitive locust was just able to stand.

"Er . . ." said his companion, eyeing this remaining patch. "Er . . . if you . . ."

The refined locust sniffed with disapproval, and delicately stepped on to the twig. As his companion devoured the last piece of the leaf in two snaps of its jaw, the sensitive locust averted its eyes. Unfortunately, wherever he looked he could see nothing but other locusts eating. He lost his appetite. This, in a locust, amounts to an extraordinary spiritual experience—indeed, it is often confused with one among human beings—and the locust felt a great desire to be on its own.

It therefore flew thoughtfully out of the orchard. As he did so he saw a party of men attack the very tree on which he had been sitting with long bamboo poles. They beat the locusts from the branches, and then swept them into a ditch. There, after a moment, they set fire to them by throwing oil-soaked brands among them. The locust watched a thousand of his companions die in less than a minute, with a most doleful sound of popping.

"What a dreadful fate I have escaped," said the sensitive locust to himself. "How dismal to end one's life with a pop! See what gluttony leads one to! How lucky I am to have refined sensibilities! Is it possible that I should have been saved from such a horrid death for no purpose? Certainly not. It is clear that I am specially chosen. But what for? Ah! I do not know. I must be patient and humble and perhaps I shall discover."

So in patience and humility he sat on a tree that commanded a fine view of the orchard, and listened to the popping until the peasants ran out of oil. Thus, although he had not been able to finish his dinner, he early learned that the spiritual life has its own satisfactions.

Sometime later in that afternoon when he was still sitting on his tree, but sleepily, he suddenly felt a violent blow on his back. He clutched at the twig beneath his legs, but immediately felt another blow, heavier than the first, which sent him reeling and tumbling through the air until he hit the hard ground at the foot of the tree with a shock which took away his senses. He awoke with a scream to find himself (as he thought) being burned alive. Within an inch of his nose was a wall of flame; the grass was burning all round him, and the heat of the ground was such that he had had to keep hopping high in the air to prevent his legs from being burned to cinders.

It was borne in upon him that he, too, was going to end his life with a pop and that it was all a grave mistake. The owner of the orchard had plainly confounded him with his gluttonous companions and was burning him—a locust with a sense of refinement and a remarkable spiritual experience—in the same bonfire as all the others.

The mere thought of this humiliation made him bound higher than ever before, and so great a hop did he execute that it carried him clear of the fire on to a raised pathway of trodden earth, and thus to safety. While he rested there, gathering his wits, one of the peasants spied him. Now this peasant owned the field on the other side of the embankment and this, so far, had escaped the locusts. The peasant, seeing a solitary locust about (as he imagined) to go into his field, raised a tremendous hullabaloo. All the other peasants came running, their long bamboo staves in their hands. When they understood what was the matter, they all set upon the locust, flailing their sticks and shouting.

The locust sprang along the path in a desperate effort to

save his life. The bamboo staves slapped the earth all round with a report which deafened him, and raised clouds of dust which blinded him, so that it was pure chance that he escaped killing at the first onslaught. But he managed to leap a little ahead of his pursuers and for a while, hopping, bounding, fluttering, and rolling along the path he managed to elude their blows. But he was soon at the end of his strength. He staggered. A bamboo cane gave him a glancing blow, and he gave himself up for dead. The next, he thought would surely kill him.

Then suddenly he felt himself taken up by the middle and raised high in the air. He was surrounded, he saw, by an enormous Hand. It smelled of sweet perfumes and was clean and smooth and the colour of sandalwood. Its fingers held him so gently that he felt no pain—only the exhilaration of being lifted so fast up into the sky. When the motion stopped he was not very surprised to find himself looking into a great, benign Face, with flowing white hair and an enormous beard.

"Do not be afraid," said the Face, but the words were very indistinct because across the mouth of the Face was a strip of linen. This was held in position by four tapes that, traversing the whiskers in four valleys, ended in loops that went over the ears.

"I'm not afraid," said the locust. "Am I dead?"

"You were very *nearly* killed," said the Face, mumbling through the strip of linen. "But nobody will hurt you now that I'm protecting you."

"No, I'm sure they won't," said the locust, confidently. "I suppose you are one of the great gods. I knew that something very special was coming my way, because I've just had what I might call a spiritual experience. It happened this way. I was . . ."

The Face immediately looked very weary.

"Yes, yes," it said. "That is most interesting, but perhaps you will tell me about it tomorrow morning when I feel fresher."

With that the great hand placed the locust next to the Face on a broad shoulder and the locust, observing the passing world in glimpses through the great white whiskers, saw that they were walking.

Soon they stopped, and the locust, holding apart two cable-like strands of white hair, saw a number of peasants. They were looking towards the Face, and some of them had their hands raised to their foreheads in adoration. The locust hoped these worshippers of his God could see him on the God's shoulder, and to make sure he trampled down a few more strands of hair so that their view of him would be unobstructed, and he gave way to a little fit of coughing.

When he saw that one or two of the peasants nudged one another and pointed to him, he was delighted. There was nothing to mar his happiness save the fact that the peasants' faces seemed much on a level with the Face that had rescued him. He had expected to be rather more elevated.

However, when the peasants laid bananas and fruits and flowers on the ground as an offering, and when the benign Face bent in acknowledgement, the locust bent his head as well, making his protruding eyes as benign as they would go.

After a while, a young boy gathered all the offerings and put them in a basket. Then the locust found that he was moving away at a walking pace as the Face left its adorers. Glancing back under one of the ears, he saw that the boy was following them, the basket of offerings on his head, at a respectful distance of twenty paces.

"They gave me all that fruit for sending away your companions," said the Face.

"Yes?" said the locust, casually, for he did not much approve of being classed with the other insects. However, he could not resist a look at the orchard which now lay behind them. As far as he could see through the thickets of hair, the locusts had left.

"They ought to be very grateful," said the locust, thinking of the peasants.

"They ought," agreed the Face. "But why to me?"

"Because you sent them away."

"*I* did?" said the Face. "As a locust yourself, how do you imagine I could send away a ravening swarm like that?"

"Because you are a God."

The Face chuckled behind its mask.

"If I were a God," it said, "you may rest assured I would not do anything so cruel and foolish as to make men with bellies and then make locusts to eat up all their food."

"Then you are not a God?"

"No."

"What are you?"

"I am trying to be a saint," said the Face.

"What is that?"

"It is a man who is so horrified at what God has made him that he wants to be something better," said the Face.

"And are you something better?" said the locust, clinging to a last hope that the Face might be at least a demi-god.

"With God's help, I think I may become so," said the Face.

"But you said," the locust pointed out, "that you didn't like what God had made you. Will He help you to change it?"

"If He doesn't, I won't," said the saint.

"That is very difficult to understand," said the locust.

"It is quite impossible to understand," said the saint, complacently. "I have thought about it for twenty-three years and I assure you it is stark, raving nonsense. Nevertheless, it is true. And so with God's help, I have sworn a vow never to take a life, not even of the smallest, humblest creature, such as you. That is why I wear a strip of linen across my mouth lest I should breathe in some innocent little flying thing. And that is why I rescued you."

The saint walked on in silence for a while. Then he heard the locust sobbing.

"What is wrong, little one?" he said.

"I can't . . . can't explain," said the locust, great tears

filling his eyes, so that they appeared to protrude more than ever. "In any case I couldn't make you understand."

"Try," said the saint. "One of the things that I have learned because I have kept my vow is the language of animals. It was not very difficult. I learned all the sad words first and so I soon understood most of what they had to say. Still, I suppose this is the best way to learn any language quickly . . ." and in this fashion he talked half to himself and half to the locust, so that the little insect should have time to recover his self-possession.

When he had done so, the locust said:

"The fact is that only a few hours ago I had a spiritual experience. Then I saw all my companions being burned alive and I was saved—call it luck, call it a miracle. I don't know. But one thing I felt certain about—I was being saved for *something*. So I waited. Then I was chased along the path with bamboo sticks and suddenly I found myself lifted up to heaven. Or so I thought. I thought you were—well not the Great God of course, but still, perhaps one of the lesser ones. But . . ." said the locust, and a sob that had remained behind from his previous tears, broke from him.

"I apologise for not being a God and for not being even one of the lesser ones," said the sage, gravely.

"Now you are poking fun at me," said the locust.

"Not in the very least. My apology was most serious, I make it every morning at sunrise."

"Why?"

"Because one should always pray at sunrise, and that is a very suitable form of prayer for a human being."

"I see," said the locust, who did not see at all. "That is very interesting and I must try it. I suppose I'd better forget my spiritual experience," and the locust essayed, without success, a short laugh.

"Oh no," said the sage. "In any case you will not be able to forget it. I know, because I had one myself. It will change your whole life."

"How?"

"It will make you," said the sage, "either a great charlatan or a great saint."

"Oh," said the locust. "What is a char-la-tan?"

"A hypocrite, a deceiver, a sham, a fraud, a man who is as happy as the day is long," said the sage.

"Then which are you," said the locust, gazing at the sage with his protuberant eyes, "a char-la-tan or a saint?"

"A good question," said the sage, ignoring the fact that it was also an impertinent one, "I have thought the matter over myself and I have come to the conclusion that it depends on the state of the weather."

While the locust felt that this mixture was far from inspiring he had to admit that its results were agreeable. They arrived at the place where the sage lived. The place was so remote that it was suitable only for a hermit; the situation was so beautiful that it was fit for a king. Here the sage lived without the pleasures of human society but in a most elegant manner, devoting his life to prayers and the cultivation of succulent vegetables.

The hermitage stood on a meadow bounded by the loop of a mountain stream. Forests rose in gentle slopes on all sides except one, and this side looked down a valley to the plain beyond. Small gardens, neatly stockaded, and sited to catch the most favourable hours of sunshine, lined the curves of the stream, each garden devoted to the growing of something to eat. The hermitage was simply constructed of poles, straw mats and plaited strips of bamboo. It had a verandah, a dining-room, a bedroom, a room for reading, a room for nothing specific, a kitchen and outhouses, from one of which came the lowing of a cow.

"I shall put you with Comfort while I go and cook the dinner," said the sage, and took the locust to the outhouse from which the sound was coming. "Comfort," he explained, "is a cow whom I have taught to speak. By speaking I mean the language of human beings. She is called Comfort because that is what she reminds you of when you look at her and

besides she never thinks of anything else. Have a quiet talk with her. Dinner will be ready in about half an hour. By the way, what do locusts eat for their evening meal?"

"*I*," said the locust, "eat practically nothing. A small leaf, to keep you company—that will do very well for me." At which the locust's stomach gave out a protesting noise. The locust blushed deeply, but was consoled when the sage showed no sign of having noticed.

Comfort, on the other hand, was plainly a cow that had never denied herself a single blade of grass. She was white. Her dewlap swung from her chin like a white curtain loaded with shot; her stomach struggled to be perfectly round, and, seen from some directions, managed to be so. Everything about her was fat except her tail, which looked as though it did not belong to her.

The sage patted her muzzle and explained in a few words how he had rescued the locust. When he said that the locust had narrowly escaped burning alive, the cow's great eyes filled with sympathetic tears. When the sage told her that the locust had been through a spiritual experience, she blew windily through her nose and shook her head in wonderment. When the sage said he must be off to see about dinner, she dribbled.

"Would you like to hear me say a few words in the human language?" she said, when the sage had gone. The locust said that he would and the cow, in a melodious bellow said:

"*Goodmorning Your Highness, Sleep well my lady, Your Majesty is quite right, I bow to Your Eminence's opinion.*"

The locust was sitting on the half-door of the stall and the tremendous rumble made his ears sing. He did not, of course, understand a word that the cow had said, and when the buzzing in his ears had subsided he asked what they meant.

"I don't think they can be explained," said Comfort, looking down the broad expanse of her nose, "to anybody who has not moved in Court circles," but in spite of this she explained at considerable length.

The locust gathered that when the sage had taught the cow to talk, the news of the miracle spread to the nearest city and a royal summons was issued that she be brought before the King.

"I was received with every mark of respect," said the cow. "Her Highness—the King's daughter you know—hung a garland round my neck with her own hands, an honour—so I was told—which is never conferred on people of lower rank than a cousin of the King. I was given a stall made of the most expensive wood and the food—I cannot possibly tell you of all the food that I was given. In the morning . . ."

But the locust begged her not to attempt so difficult a task: protesting winds were blowing through his abdomen.

"And you talked to all these important persons?" asked the locust.

Comfort replied:

"Oh yes. Frequently."

"I should have died with embarrassment," said the locust. "I wouldn't have known what to say at all."

The cow said nothing, but merely lowered her eyelids, and chewed her cud with what the locust found an irritating composure.

"I suppose the sage had given you plenty of instructions," said the locust.

"Oh, yes," said Comfort. "Some."

"What did he teach you?" asked the locust.

"It's a long time ago," said the cow, "and my memory is not very clear on the point. But I recall that he taught me a piece to say about 'How a wise man should act when his Duty would seem to conflict with his Destiny.' "

"What a fascinating subject," said the locust, the two knobs that were his eyes glowing. "That is just the sort of conversation that I have always longed to hear. Well, how does a wise man act when his Duty conflicts with his Destiny?"

"Eh?" said the cow. "Oh, well, he . . . follows his nose, I should say. Yes, follows his nose," she repeated, chewing

rhythmically. "I can't remember if that's what the sage said —it was all a long time ago—but that's what *I* should say."

The locust looked a little disappointed, but he persisted. "What else did the sage teach you?"

Comfort chewed until the locust began to think that she could not have heard the question. He was just about to repeat it when she said, swallowing heavily:

"There was a piece I was to use if any Brahmins came to talk. I recall that it began: '*Is the earth, which is supported on a tortoise, round or flat?*' "

"How exciting!" said the locust. "And is it round, or is it flat?"

"Don't be silly," said the cow, beginning to show impatience, "of course, it's flat. Just look at it. Flat as one of my pancakes."

"I am sorry if I am annoying you," said the locust, stiffly. The cow, he could see, for all its experience of polished society, was still, at heart, vulgar.

"No, no," said the cow, chewing calmly again. "You're not annoying me. But to tell you the truth I never did talk about these things: not at Court, I didn't. I chose my own subject and it went down very well. All the really important people were very pleased, although I must say that the sage was very annoyed. I think," she went on, "that living here all alone, the good man had got out of touch with the way that good society behaves."

"What was the subject that you chose?" asked the locust.

"I didn't really choose it. It just came," the cow replied. "In the give-and-take, you know, of my social life. But then perhaps you don't know." With which she chewed, more exasperatingly than ever.

"I don't know anything," said the locust. "That's why I'm asking." It was not the sort of reply that the locust would have made in his more collected moments, but the circular movement of Comfort's jaws was unnerving.

"Asking what?" said the cow.

"What you talked about," said the locust, in a manner which showed he was not to be fobbed off.

"Well, if you want to know," said the cow, and pausing lowered its eyelids. "The subject always seemed to be . . ." She paused.

"Yes?" said the locust.

"Bulls," said the cow.

Neither of them said anything more for a while, and then the cow went on, in justification:

"I can see you agree with the sage. Well, I don't say it was the best topic from the point of view of improving the mind. I wouldn't have thought myself that it was really up to me—a cow, you know—to improve the minds of the royal circle: although in fairness I must tell you that that was just what the sage had in view when he sent me. All that I do see is that my recollections of—well, as I say—bulls—seemed to suit the court like a glove. The courtiers lined up to talk to me, and the Princess—well—at meal-times Her Highness had to be dragged away by her ladies-in-waiting, who didn't want to go either. They'd all have eaten in my stall if Court etiquette had not forbidden it. But of course, there was the sage, getting more and more angry with me. Then there was the Chief Brahmin."

"Didn't he like your—your style?" said the locust, with a very keen look out of its enormous eyes.

"I can't say whether he did or whether he didn't," said the cow, opening its own eyes very wide. "He said that I was corrupting the manners of the Court and I shouldn't be allowed to talk . . ."

"Ha!" said the locust, with open satisfaction.

". . . unless," the cow went on, "I said everything I was going to say to him, each morning, for his approval. He didn't approve, but how he listened!" said the cow, and munched with reminiscent pleasure on her cud.

"And then what happened?" said the locust.

"The sage came and took me away," said the cow, with simplicity. "Her Royal Highness wept and she stormed and

she even stamped her foot at the King. But he wasn't sorry to see me go. I think he felt I put him in the shade. Besides, he arranged for Her Royal Highness to be married straight away to put me out of her mind. But, do you know, on her wedding day she sent me—all the way to this hermitage, by royal courier—a great big bunch of flowers, which I ate, and my, how delicious they were."

The cow ran her vast tongue round her mouth and lowering her eyelids, shook her head at her happy memories. This was more than the locust could bear, and, excusing himself abruptly, he went in search of the sage to see if dinner was ready.

VII

The Tale of the Studious Locust continued

It was ready, and it was a banquet. The sage had piled leaves higher than his guest, even if his guest stood up on its hindlegs, and next to this he had laid out smaller heaps of buds and tender shoots. For himself the hermit had set a banana-leaf heaped with rice, while around the leaf he had arranged a semi-circle of small bowls, each with a different curry. A gleaming pot of bell-metal was full of Comfort's milk, and a wicker basket of fruit made the table's centre-piece. The locust had punched a whole leaf full of semi-circular bites before he remembered that he was a locust with a sense of refinement. With reluctance, but an indomitable will, he stopped eating. Only when the sage had begun a conversation did he resume, and then delicately, a nibble here, a nibble there, as though he ate not from hunger but politeness.

"Now tell me," said the sage, "what did you think of Comfort?"

"Very well-meaning," said the locust, "but perhaps not very brainy. She must have been a disappointment to you."

"No," said the sage. "I learned a great deal from her, and I am most grateful."

"What did you learn?" asked the locust.

"Never to teach philosophy."

"To cows, of course."

"No," said the sage, "to courtiers. It has saved me from wasting a great deal of time."

The locust nibbled a last shoot, and then walked a pace or two away from the pile of food to show that he had finished.

"I have something to ask of you," he said. "But I'm afraid that you'll think that a waste of time, too."

"I hope I shan't," said the sage, "but have you finished eating? You've taken very little. Perhaps I've picked the wrong kind of leaves?"

"They are delicious," said the locust.

"I always understood that locusts had large appetites," said the sage.

"They have," said the locust.

"Then aren't you hungry?"

"Yes," said the locust, and swivelling his large eyes full upon the sage, he said, "But my hunger is not for food: it is for wisdom."

The sage was suddenly taken with a fit of coughing. After it was over he wiped his eyes.

"Forgive me," he said, "I bit on a chilli. Please go on. You were saying that your hunger is for wisdom. So . . .?"

"So I would like you to teach me all these things that you tried to teach that foolish cow," said the locust, passionately. "Ever since I was born I have felt that I am different from the other locusts—yes, superior to them—I'm not afraid to use the word. And now that I have had my spiritual experience I'm sure of it. Oh, I know that you are thinking that I will turn out no better than Comfort. I know that you think that after all your labours I'll just give way to my baser instincts and . . ."

"But you know you won't?" asked the sage.

The locust paused. He studied the sage's face. He thought that he detected a smile on the sage's lips, but it was difficult to be sure because at that moment the sage, having finished eating, slipped his mask back into place.

"Yes," said the locust. "I know I won't. And to help you believe me, I promise that every day that you teach me I shall eat no more than I have eaten today. You yourself have said that locusts have large appetites. This one has also got self-restraint. Four leaves, two buds, and a piece of stalk, every day that I have a lesson. Master, is it a bargain?"

"Little friend," said the sage, looking down at the locust over his mask with his dark brown eyes, "it is a bargain."

Now began a time of contentment for the strong-willed insect. The sage did not teach him to speak a human language: neither he nor the locust saw any purpose in so difficult a task if it were to end as it had done for the cow—but he taught him to read. The sage would prop the long palm-leaf books against some jars, and the locust would walk slowly in front of them spelling out the words that had been cut into them with a sliver of metal. Sometimes the sage would dip his finger into charcoal powder and rub it across the letters, blackening them, and making them easier to read. Sometimes he would untie rolls of kid-skin and the locust's round eyes would grow rounder still at the blaze of gold and vermilion on the inside of the leather, a meaningless splendour to him until he learned the trick of seeing the flat design as pictures. That learned, he went on many voyages into marvellous countries, saw many gods and kings and philosophised over many beautiful women, all without leaving the floor of the room that had once no proper purpose, but which was now the locust's own.

From these simpler books he progressed to more profound studies. He learned that there were ten ways that a Brahmin may praise the gods on rising and only one way in which he may defecate. After weeks of patient application he learned why it was certain that the earth was supported by a tortoise, but that nobody knew what supported the tortoise. He studied six different ways of burying himself alive for twenty-one days and not one reason why he should do any such thing. He read the lives of the three great rishis who had devised fifty-eight flawless constitutions for the governing of a State and did not know what to make of the fact that none of them had been asked to govern anything bigger than the collection of mud huts immediately next to their hermitages.

Under the sage's instructions he learned the principles of

good painting in the books of a man who could not draw, the art of good writing in a book which was unreadable, and the essentials of good music from the analyses of a man whose music nobody had ever sung. He studied history in great detail and found that the reason why kings lost battles was that the opposing kings had more brains and better troops; he was instructed in the fact that the reasons why States went bankrupt was that their rulers spent more money than they had got; and after titanic studies he was satisfied that a thorough knowledge of the past could lead a profound scholar to predict the future course of history with great accuracy, provided that it did not turn out quite differently. He became, in a word, well-educated.

He also became hungrier, and hungrier and hungrier. The sage, who found that keeping his side of the bargain was more exhausting than he had anticipated, hoped each day that the locust would not keep his. The sage spent what time he had to spare from instructing the insect in searching out the most tasty leaves and juiciest shoots, which he arranged in a tempting fashion in small heaps, one very close to the other, so that the locust might be led, unthinkingly, to go from one to the other and eat more than the agreed amount. This the locust did not do. He would divide out the piles and separate the exact quantity of food which the bargain allowed for, and, having eaten it slowly (but with a set expression) he would return immediately to his room and his studies.

But as he grew more famished he grew shorter tempered. As his temper grew worse he felt the need to quarrel, which the sage, looking down at him with his great brown eyes, always refused to do. This drove the locust to seek the company of the cow. Comfort, if not of a quarrelling disposition, was fond of making downright statements and these gave the locust a chance to attack her sloth, her ignorance, her base yielding to the life of the senses, and her general failure to take the great opportunity that had once been offered to her, at the same time comparing her conduct

with his own devotion to his studies, his austerity, and his rising above the temptations of the flesh. Then, for the hundredth time, he explained how he had been elevated above all common insects and animals by his spiritual experience.

The cow found this last very wearying, but she discovered by experiment that she could infuriate the locust to such a degree that it was deprived of words and went away. This she could do merely by slowly, rhythmically and ostentatiously chewing.

One day the locust, thus enraged, flew away beyond the confines of the hermitage, not really knowing where he went, so plagued was he by hunger and so exhausted by study. He flew down the stream and into the broader reaches of the valley.

He returned that evening at dinner-time. The sage greeted him. The sage enquired how he had progressed in his studies. The sage asked solicitously if he did not feel unwell. To all these questions, the locust made no other reply but a loud hiccup.

The sage was mild, but terrible in his glance.

"Where have you been?" he said at last.

"The . . . fields," said the locust, and was once more shaken with a hiccup.

"To study, perhaps," said the sage, "the structure of newly growing leaves?"

"In a way," said the locust, and hanging his head, he hiccuped violently three times.

"Possibly," said the sage, "by eating them?"

"Possib . . ." said the locust, but could get no further, partly from the explosions of his hiccups but more from utter shame. He took one last look at the sage, but finding no hope in his venerable face, the blushing insect crawled to the door, and flew away from the hermitage, never to return.

VIII

The Fight in the Glade

THUS warned, Rama still pursued wisdom, but with moderation. He made the acquaintance of the other Gluttons, among them a tall, spare, and venerable man called Jabali, the founder of the Hermitage of the Gluttons, but himself a man with a delicate stomach who lived largely upon curdled milk. Of this, following his principles, he took more than he really wanted, but it did him no harm.

Jabali's disposition was mild and kindly; the years he had spent in meditation gave dignity to his bearing; his diet gave sobriety to his conversation. He was immensely learned and made light work of answering all of Rama's questions. The advantage of the hermitage was that Rama had only to cross over to a neighbouring hut to have it proved to him by another hermit that all the answers were wrong.

Some months passed in this peaceful fashion. Rama was contented, Sita dutiful, and Luxmun bored. Luxmun was sure, as always, that whatever his brother did was right, but he was disappointed to find that doing right did not include an occasional fight. He had hoped to defend his brother from enemies, and now, while the hermits split hairs, Luxmun longed to split heads.

Rama rebuked him. Luxmun, disconsolate, went to talk over his troubles with Sita. She had taken on the duties of running Valmiki's hermitage (for Valmiki was now wholly absorbed in his poetry) and Luxmun found her working with the boy in the kitchen.

"Rama is angry with me," said Luxmun, "because I want to do some fighting."

Sita stirred the rice which was cooking in a large copper bowl.

"Yes," she said. "He has told me. He says that if you kill a man it's the surest way to lose your chance of becoming a real philosopher."

"H'm," said Luxmun. "I know a surer way."

"Do you?" said Sita absently, as she stirred the rice. "What is it?"

"Let the other man kill you."

Sita smiled, then yawned, and then stifled the yawn. She picked the rice grains off her wooden spoon to see if they were each separate, as well-cooked rice grains should be.

"Well," she said, "there's not much danger of anyone wanting to kill you here."

"No," Luxmun said, grumbling. "And even if some small war should break out I can't see any of the soldiers troubling to attack a lot of argumentative old men."

There, however, he was wrong.

Whenever the thought of another day in the hermitage had grown unbearable to Luxmun—with Valmiki muttering verses, the hermits wagging disputatious fingers under one another's noses, and Rama in a brown study—it was his habit to take his spear and stride off into the surrounding forest, not caring where he went but allowing the jungle paths to lead him, and turning back when the sun was half-way down, finding the hermitage by tracks, or the moss on the north side of trees, or by his hunter's instinct.

One day he had gone further than usual because his temper had been worse. He had spent the evening before in an attempt to persuade Rama to make a journey round the courts of neighbouring princes and to gain their aid in raising an army with which to return to Ayoda and claim his birthright. But Rama had argued that he was enjoying the only birthright that he cared to claim—namely, peace of mind and freedom to think. Luxmun had left him abruptly, not trusting his tongue.

Now he was walking through an open forest of smooth teak trees that stood, every so often, round small glades set with flowering shrubs. One such glade led, by means of a narrow path between two rows of bushes, to another and much larger glade, that caused Luxmun to stand still in astonishment.

The glade was smooth and scattered with flowers. At one end rose a cupola of white marble supported by slender columns, also of marble, but marble of a yellow hue. Between these columns and hiding the interior ran a screen of filigreed metal, worked in a design of flowers and leaves and imaginary animals. Between the two front columns, the screen was taller to allow for two doors, also of filigree, one of which now stood open. The whole structure though strongly built was no larger than a tent and was clearly a summer house, as could be seen from the marble steps which led from the doorway into a stone pool filled with water. The glade and the cupola had the appearance of being cared for, but there was no sign of an occupant.

Luxmun, standing between the last of the bushes at the end of the entrance path, called out. Some birds flew up, but there was no answer. He called again and thought that he heard, deep in the trees behind the cupola an answering voice. But a third call brought no reply, and Luxmun, advancing into the glade, knelt down by the stone pool. He laid his spear aside on the grass verge, and began to drink, cupping his hands. But the water lay well below the level of the stone edging, and he could not easily bring it to his mouth. He lay flat and took off his bronze helmet, the only sign of his calling that he wore, since otherwise he was dressed in the loin-cloth and sandals of a hunter.

As he dipped his helmet into the water he was struck a heavy blow between his shoulder-blades. He cried out with pain, and loosening his grip on the helmet, it fell into the pool. Another blow, even heavier than the first made him roll over on his back, gasping.

A tall man clad in black armour stood over him. He was

holding a javelin close to its metal cap and he had swung it back to give Luxmun yet another stroke. A helmet, of fine mail like his metal jerkin, and lacquered black, came down low over his forehead and carried a vertical bar that covered the man's nose. The staff of the javelin fell upon Luxmun's ribs as the man threw out his other hand in the contemptuous gesture used when ordering inferiors to go away.

The man's armour proclaimed him a noble; Luxmun saw that he had been mistaken for a forest huntsman of low caste who would pollute the water by drinking from it. As the blows fell on his sides and shoulders, Luxmun, shouted: "My helmet! Let me get my helmet!" for this would be proof of his rank. The man laughed and swinging the javelin behind his head poised himself for a final blow.

Luxmun, enraged, reached for the hilt of his hunting knife, at which the man brought down his javelin staff across Luxmun's fingers.

Luxmun rolled over in agony and the man still laughing, kicked him. Luxmun seized his spear and flinging it upwards with all his might struck the man in the black armour a blow upon his shoulder which, though turned aside by the mail coat, sent the man reeling backward. His fingers still numb from the blow, Luxmun drew his hunting knife, shouting, "I am Luxmun, Prince of Ayoda—defend yourself."

The man in black armour had a short warrior's dagger at his belt and this he drew, closing with his adversary as Luxmun rose from the ground. Luxmun seized his wrist and the man countered by taking a grip upon Luxmun's forearm of tremendous force.

They struggled in this fashion, their faces close together, for a few moments, and Luxmun knew that he was fighting a man of a strength such as he had never before experienced. But rage and anger gave Luxmun an advantage over the other, who had been surprised at the ferocity and boldness of the huntsman's assault upon him. Even so, the man in the black armour, straining his knife towards Luxmun's unprotected breast, suddenly scored the flesh so that Luxmun's

blood spurted out over the man's forearm. Luxmun exerting all his strength to save his life, forced the other man back a pace and then another. Thus stumbling and reeling, they drew near the cupola. Luxmun's bodily strength protecting him, but his numbed hand refusing to answer as he tried to drive his knife home.

The columns that held up the cupola stood on a plinth that projected some distance beyond their bases. Driven against this, the man in the black armour reeled heavily backwards, his shoulders pressing against the metal trellis. He slipped, gained his footing on the plinth, and eased his shoulders upward against the grills. But Luxmun pressed him with all his might and in a moment the thin metal buckled and gave way. Both men fell inwards under the cupola; the jagged points of the broken metal tearing at the flesh of Luxmun's arms. As the man in black armour fell he called out in a loud voice for aid; Luxmun heard answering shouts and the sound of men running in the forest.

Luxmun shook himself free from the prostrate man. He turned his back upon him, ran swiftly to the pool, and plunged his arm into the water, searching for his helmet. The pool was terraced in a series of steps that led down into the water and Luxmun groped blindly. The man in black armour, still shouting, had got to his feet. A javelin struck the stone edge of the pool beside Luxmun and bounded the full width of the water, humming in the air. Luxmun leaned over further and as another javelin passed over him, his fingers closed round his helmet. He rose, and flung it at his adversary's feet as a gage. Then, seeing armed men at the further end of the clearing, he turned and ran swiftly to the bush lined path by which he had entered. He struck out with his knife at a man who, breaking out of the forest tried to stop him, and felt his knife jar upon bone. The man shouted in pain, and fell back. Luxmun, leaping between the bushes, ran down the path, across the smaller glade and so made good his escape.

When Luxmun regained the hermitage covered with blood, the philosophers were very upset but Luxmun was serene. Rama ran to him as soon as he saw him, and supported him for the last few yards to Valmiki's house (for Luxmun had no strength left in his legs) but all the while Luxmun talked with calm good-humour about his fight adding, now that his anger had gone, a good deal of praise for the strength and agility of the man in black armour. When Rama and the philosophers exclaimed at his wounds, Luxmun told them that he would not have returned at all if his opponent had not lost his balance on the plinth of the cupola.

Hearing this, Valmiki, who had hurried from his room to see what help he could be, asked Luxmun to describe the cupola more clearly. Luxmun, resting now indoors, did so as best he could while Sita bathed his wounds.

Valmiki looked grave when Luxmun had finished.

"You say," asked Valmiki, "that you threw him down on his back."

"Yes."

"That was bravely done," said Valmiki. "Nobody has defeated him since the day of his birth. You have made the most implacable enemy in all India. Now you must rest: you have been for a long walk," said Valmiki, "and if I am not mistaken it is not yet finished. The name of your enemy is Ravan."

The hermits who had crowded anxiously into the room fell silent and looked at one another in alarm. Then Sita took Luxmun to an inner room and the hermits left. As they walked past the open window of his room, he heard the name "Ravan" several times spoken in a low voice, and later its syllables tolled in his dreams like a sombre bell.

He awoke to find Sita and Valmiki bending over him. Valmiki, with a gentle hand, was rubbing a salve into his wounds. He had, he said, just made it from herbs in his garden, and it was still warm from the fire. Beyond a pain where Ravan had struck his hand, Luxmun felt no worse for his adventure, and he was much refreshed by the sleep.

Valmiki left them. Sita, having seen that he needed nothing, sat on a rush mat near the bed and opening a small box began to prepare him a betel-nut to chew. She took the leaf, spread lime on it with a spatula, powdered this with ground spices, then folding the leaf, pinned the small bundle together with a clove. Luxmun took it and chewed contentedly, savouring the sharp dry taste of the spices.

"He's a fine fellow, this Ravan," he said, seeking a chance to talk about his fight.

"I know," said Sita. She began to prepare another leaf.

"Stands taller than me," said Luxmun.

"Yes," said Sita. "I know."

"As far as I could see, he's handsome in a fierce way."

"Yes," said Sita. "I think so too. And he is not always fierce."

"I wonder who he is?"

"He is a king. Not a big king; but still a king. He is the Lord of Lanka."

"A *king*?" said Luxmun, sitting up with surprise. "But how is it that you know so much about him?"

"He is in love with me," said Sita, and smiling, she offered him a second leaf of spices. He refused it and insisted that she explain.

"There's not very much to explain," said Sita, "I . . . well, of course, I'm very happy to be here because my husband is very happy to be here, but sometimes I do get tired of . . . no, that's silly, because a wife can't get tired of doing what pleases her husband. Still, sometimes I . . ." She stopped. Luxmun continued for her:

"Sometimes you are so bored that for two betel leaves you'd chase the next philosopher round the hermitage with a ladle," said Luxmun. "I understand that very well. What I always do when I feel like that is to go for a very long walk."

"So do I," said Sita.

"I've never noticed."

"No," said Sita. "Of course not. Why should you?

Though I suppose—at least I hope—somebody would notice if I didn't come back," she said: but observing that she was growing wistful (a ruinous mood, in her view, for a princess in misfortune), she put the leaf of spices in her mouth, and chewed upon it in a masculine fashion. "Well, then," she resumed, "I went for a long walk one day along the road to the south, and I came across a party of soldiers eating by the wayside. Their leader saw that I was alone. They were rough men, rougher than our soldiers back home. I was afraid. But he stood up and ordered his men to stand as well. He asked me if I was in any trouble. I said no. He said it was strange to see . . ." She hesitated.

"Yes?" said Luxmun, "go on."

". . . to see a lady of noble birth walking alone, although how he could see that I was, I can't say, because I was dressed as I am now," and she looked sadly down at the stains on her sari. "I told him as much as was necessary. He made me rest and gave me something to drink—wine, I think it was. Then he, with about six soldiers walking behind, came back with me, but not all the way. He said that he would not cross the boundary of his kingdom, and that's how I found he was a king. Though, of course, he told me so when we met after that."

"You met him again?"

"By a small ruined shrine that has a pretty jacaranda tree," said Sita. "I should not have gone, but he talks so well and he never says, 'On the face of it what you say is true, but if you look deeper you'll see that you are mistaken,' like all these wind-bags here. Yes, I saw him again. Three times." She looked sideways at Luxmun and saw that he was frowning.

"Yes," she said, "he is indeed very strong and a good deal taller than you. I think it is quite wonderful that you managed to beat him." Looking up again she saw Luxmun no longer frowned, but beamed.

"A king, you say. Where is Lanka?"

"It's a town, he says. Not very big but with very thick

walls. You go south along the road, through a great forest—that's why I've never been to see myself—and you come out on a plain and there it is," she replied. "I should like to see a town again, and hear the noise, and the temple gongs, and see the markets and the silks and the jewellers—just for five minutes."

"So should I," said Luxmun, and lay back on his couch, thinking not of silks and jewels but of a walled city whose king he, Luxmun, had already once defeated: a king to whom he had thrown a challenge.

The walls of Lanka rose straight from the plain. There was no moat, perhaps from lack of a river to divert. But the walls themselves, high, crenellated, and ponderously thick, stood in no need of any other defence than their strength. They hid all but the higher roofs of the town within and the walls, in their turn lay half-hidden behind slighter walls, cunningly disposed in lines and quadrants, to wear down the attacker before he could come within javelin cast of the main fortifications.

Luxmun surveyed them closely from the shelter of a small wood some distance away. He could go no nearer for fear of being recognised. Between his wood and the city there was nowhere to hide: all had been swept clear so that anyone approaching should be in full view of the watch-towers.

Luxmun turned back. He had satisfied himself that the man he had challenged was truly a king and the king of no mean city. To recover the helmet that Luxmun had thrown at Ravan's feet as a gage would need an army.

It had been a grim journey. He had set out upon it as soon as his wounds were healed, telling nobody of his intention. He had found the ruined temple, the place of Sita's meetings, but here he had left the road, and asking his way from a peasant in the fields, made a great circuit outside the boundaries of Ravan's small kingdom, lest he should fall in with soldiers. Then he had come upon a village, the shells of its huts still smoking, and bodies, covered with

blood, waiting to be burned upon funeral pyres of their own beds and boxes. He was told that Ravan had crossed his boundary on a raiding expedition the day before. The headman had refused homage and had been cut down. Retiring from their foray, Ravan's soldiers had driven the cattle they had stolen over the bodies of the villagers they had killed on their way to their raid. When Luxmun expressed his horror, the villagers pointed to smoke on the horizon and told him that there they had done far worse, and killed more slowly. It was the season, they said, for Ravan to make war.

Luxmun returned to the hermitage, and told only Valmiki of what he had seen.

Valmiki said:

"He is a cruel and bloodthirsty robber. Now that Rama has brought us gold, I think maybe he will come here. We should make fine sport for his soldiery."

"But not," said Luxmun, "before I have given them some sport of my own choosing."

IX

Sita's Rape

RAVAN burned down the hermitage of the Gluttons on the night of the next new moon.

His soldiers opened the attack in silence. They climbed trees in the surrounding woods and came up over the brow of the hills behind. Then they shot arrows tipped with burning pitch into the thatches of the semi-circle of huts.

Valmiki was the first to wake. Seeing the roof of the neighbouring house burning, he shouted to wake Rama and the others. In answer there arose the bray of war trumpets and a pulsing howl, deliberately animal and thus doubly terrifying, as the soldiers streamed from the woods and down the hill-sides, kneeling every so many paces to loose arrows into the conflagration.

As the first soldiers ran up the path that led to Valmiki's house, Rama came out from his room. An arrow struck the wall behind him and as he turned away to look at it he heard the animal-like cry, but close at hand. He turned back to see a tall soldier, grimacing with the effort of the war-cry, standing not twelve feet away. His right arm was flung back ready to launch a short spear at the house. Rama, unarmed, stood irresolute. The man bellowed again but this time his cry rose to a scream. He stood for a moment rigid and then fell sideways. An arrow protruded from his left cheek.

"I can't expect such luck with the rest," said a calm voice behind Rama, "so I suppose I'll have to use my head, and that's something I never like doing."

Rama turned to see Luxmun kneeling outside the doorway to his room; his bow was still trembling from the arrow which he had just loosed. He stooped, took another from where it lay by his knees, and sent it after the first, but

a little higher so that it fell among the fallen soldier's companions. These, hearing the unmistakable sound of a warrior's bow, fell back, and turned their attention to more peaceable huts.

Valmiki came to the verandah, his arms round the woman and the boy who were his servants. Luxmun told Rama and the others to go into the room behind him. He did not move his stance, but allowed them to step past him as best they might while he sent arrow after arrow towards the great tree. Sita, behind him, handed the arrows to him as he needed them, stroking the feathers on the shaft into place as she did so.

When all were in shelter behind him Luxmun said:

"The house is as good as gone. Even if it doesn't catch fire they can still surround us. I can hold them here in front, but they'll come hopping down the terraces behind like a crew of monkeys. Brother, take the javelin you'll find next my bed and your bow; Sita, bring the rest of my arrows; Master Valmiki, get your poem or these barbarians will use it to fry their fish. I know soldiers. I am one. I shall bring the gold. All of you, go, please, to the carob tree on the terrace, lie down, and wait for me. Aha, you damned jackal," he ended, as evenly as he had spoken all along, and the shadow that he had thus addressed ran screaming into the darkness, tugging an arrow from its middle.

When they had obeyed him they could see, as they lay among the great roots of the carob, the sack of the hermitage. A half-circle of fires marked the huts. Here and there a naked or near-naked hermit lay sprawling on the earth. One had a spear through his belly pinning him to the ground. With horror Rama saw that the man's limbs still moved.

Then he saw the mild and venerable Jabali, he who had answered all his questions, driven naked with obscene thrusts and pricks of a spear towards the great tree. There he was made to bow down to the ground before a tall man in black armour who was taking no part in the sack, but

who was directing it with shouts and encouragements to the soldiers.

"Who is that?" asked Rama, and Sita, staring fixedly at the man, said:

"Ravan."

Luxmun climbed the steps that led to the terrace, grunting with the effort of carrying the mule-bag of gold. He warned Rama to watch the hill behind them, from which they were separated only by a low wall that was fully commanded by the slope of the hill. Then he returned down the steps for the second bag, refusing any help.

Rama watched the dark hill for a while, but a burst of laughter from below him drew his attention.

One of the soldiers by the tree was now performing a clumsy imitation of a male dancer and his companions with the help of their javelin points were forcing Jabali grotesquely to follow his movements, as though he were a woman. When he tottered, they dragged him upright by his beard, tearing out the hair. The tall black figure of Ravan did not move during this savage game, but Ravan watched and did not stop them.

"They must be drugged with hashish," said Rama.

Valmiki shook his head.

"Hashish takes a man out of himself," he said. "These have needed nothing. Perhaps a little wine, to make the blood run faster. Nothing else."

Luxmun returned to them with the second bag and, himself took charge of watching the hill. Seeing, as he thought, a shadow move, he drew his bow but the bowstring snapped under his fingers. He asked the boy to go down and get another, but the boy, trembling, could not move for fear. Valmiki said that he would go, but Sita forestalled him.

"If they attack, a woman will be no use here. I shall go and fetch it," she said and when Rama protested she said that it would be safe for a while, since the soldiers were busy tormenting the old man. Before they could stop her, she had gone.

They began shouting under the tree and Rama saw that Jabali had fallen prone on the ground. A soldier was beating him with a spear-butt, but Jabali did not move. Then the soldier reversed the spear and jabbed it repeatedly into the old man's shoulders. His victim began screaming.

Rama, maddened with rage, got up, shouted, and drawing his bow, shot an arrow. The light of the flames shone on his bronze figure, and flashed from the mounts of his great bow.

The arrow fell far short of the tree. But Rama's shout had been heard by the soldiers and they now stopped their torture of the philosopher and gazed up at the terrace.

Then Rama saw Sita walk across the space between the house and the tree, go up to the soldiers, pass among them, and bow to Ravan. The man in black armour bowed profoundly in his turn, and Sita and Ravan appeared to talk.

Jabali, bleeding, crawled away.

"They'll come at us now," said Luxmun.

But the soldiers did not. Some shouted; others loosed arrows up at the terrace, but wildly, as if jesting. Sita and Ravan still stood together.

Then a horse was brought from the woods beyond the hermitage. Soldiers held it steady for Ravan to mount. When he had done so, he reached down his hand to Sita who took it. Soldiers assisting her, she mounted the horse behind the man in black armour, and together they slowly rode away.

The soldiers, picking up their bows and lances, followed in a disorderly group. In a few minutes the watchers on the terrace could see no more sign of them.

Not daring to speak to one another Rama, Luxmun, and Valmiki went down and, in the light of the fires, they succoured the wounded and covered the terrible postures ot the dead.

Forlorn, bleeding, with some wandering on their wits, the surviving hermits were shepherded away from the

blackened hermitage by Valmiki and the princely brothers. Valmiki led them some miles to the town of a nobleman, a self-styled prince, with a tiny Court and much pomp, or as much pomp as his annual tribute to protect himself from Ravan would allow.

Hearing Rama's name, he welcomed the fugitives. When they had rested in the ornate little palace for a day, Luxmun showed their host the gold that Ravan had not been able to find. Then he, speaking through the lips of the nobleman, showed Rama the only path that was honourably left to him. With his gold, he could rally the nobles, the rajas, and the princes who had suffered for many years under the royal brigandage of Ravan, and lead them to their revenge on Lanka.

There was no gainsaying the nobleman's argument and, well grounded by Luxmun in Rama's way of thinking, he put his points well. Since Rama had not taken the saffron robe, he was still a prince, and a prince whose wife had been stolen by a petty, if formidable, raja. He must redress the injury, or forfeit his rank in the eyes of his equals, a thing which was not only a disgrace but a sin against the commandments of the gods. The gold would start an alliance which would soon grow of its own accord into a great army. But great armies needed a leader and the allies would fight among themselves if they were left to choose one from their own ranks. Rama, with Sita stolen, was the choice above all contention.

Rama bowed to this reasoning. Luxmun, well pleased with his work, instantly set out in Rama's name to the surrounding rajas, and began his work of persuasion and bribery.

"But," said Rama, again and again to Valmiki in the long weeks of waiting that followed, "she was *not* stolen. I saw what I saw. She went willingly on that blood-soaked monster's horse. I saw her. I say, I saw her. What am I to think?"

It was plain enough from his looks and gestures that he had already made up his mind what he should think of her flight: and when Valmiki's servant told him·that Sita had once said that she had met Ravan in a ruined temple, he did not attempt to hide the rage of jealousy which was eating at his heart.

He was sitting one hot night with Valmiki on a small terrace that the nobleman had built in imitation of the cool promenades of marble which greater princes had on palace roofs. He said to Valmiki:

"Everything that I set out to do when I left Ayoda has been brought to nothing. I am not a philosopher. I am a warring prince. I am not a hermit: I am living in a palace: and I am not chaste as the sages say one should be, but I am on fire with jealousy. I think continually night and day of what she may be doing, what I fear she must be doing, in Ravan's bed. But still, I have learned some few things, and I have grown more than a little wiser. Looking back, I see that this is due to your instruction. Have you anything to say that can cure a man of this base passion of jealousy?"

Valmiki thought, then smiled his deep smile until it grew into a grin.

"I have nothing to say about the passions of princes of royal blood. Such things are too great for me. But I do remember the advice that was given to four fishermen and since it came from a god it should be worth considering."

"I shall be glad," said Rama, "to hear any advice that comes from a god. Tell me what it was."

So Valmiki, to lighten Rama's dark thoughts of Sita and Ravan, began the tale of the four jealous fishermen and their nocturnal adventures.

X

The Nocturnal Adventures of the Four Jealous Fishermen

THERE were once (said Valmiki) four fishermen who led honest and simple lives and fished in the Rann of Kutch. Their names were as simple as their lives. They were called Luckyman, Stumbler, Quickly, and Shy. These were the names that the other fishermen called them by, and if they were neither ancient nor dignified names, they fitted. Luckyman was a handsome young fellow for whom everything went right. Stumbler was square and slow and was never sure of his feet or himself; Quickly was forty and knew all the tricks of fishing—it was a pleasure to watch the deft way he worked a boat; while Shy, the youngest, was shy.

They lived in a village which was built on a mud-flat. It faced an inlet of the sea which was flatter than the mud and even more dull to look at. There was nothing whatever in the village or its surroundings to take the fishermen's minds off fishing, except, their wives.

Now Luckyman, Stumbler, Quickly, and Shy all had wives of considerable beauty. It chanced that way; there was no design in it. Their wives had been chosen by their parents and their parents had chosen the girls because their dowries were the best bargain going at the time. Luckyman, Stumbler, and Quickly had been married when they were seven, but Shy had been made to wait until he was twelve because he, by some freak, matured late. The dowries that Quickly and Stumbler received were much less than Luckyman's haul: while Stumbler's wife tippled. But in spite of these differences, in the matter of womanly attraction, there was nothing to choose between them. Luckyman, Stumbler, and

their two companions were all as proud of their wives as they were of *The Dancing Woman.*

This was their boat. They had built her themselves and she had cost most of the four dowries: but she was a beautiful boat, as sleek and quiet in flat water as a well-fed buffalo, and when she got into the ocean leaping to the waves so gracefully that she seemed to arch her back. She was black, with two painted eyes in her prow, a lateen sail, and a high red tiller. In front was a boom, bright yellow, from which they hung the iron basket that carried a fire. The fishes would come to look at the fire and while Quickly steered the boat in a circle, Luckyman and Shy paid out the net and Stumbler watched that it did not foul. Then they would hit the sides of *The Dancing Woman* with sticks to frighten the fishes. An hour of this, and then all four would haul the net aboard, the fishes tumbling out of it, gleaming in the light of the fire like the money that the fishermen earned next morning.

But there lay their trouble. They had to fish at night. They launched *The Dancing Woman* at sunset and they did not turn her prow for home until the light began to whiten the sea. Then there was the selling to do. This called for a long cold trot across the mud-flats with the baskets swinging from poles across their shoulders, then a haggle with the merchant, and much standing around maybe for an hour shivering in the wind from the sunrise, while the merchant wrapped his woollen shawl about him and beat them down till their toes were blue. After that came a long trot back home to a sleepy wife blowing up the charcoal fire to cook breakfast—a welcome sight, no doubt, but only if you could be sure that she had slept on her own, as a good wife should, all the previous night.

But could they be sure? This was the question that vexed Luckyman and Stumbler, Quickly and particularly young Shy, whose wife was the youngest of all and therefore the most tempting. When the boat was running well, when the fish broke the nets with their weight, when even the mer-

chant forbore to screw them for the last rupee, neither Luckyman nor Stumbler, Quickly nor Shy, could be happy. This doubt prevented them.

Sometimes Luckyman would be staring down into the water where the light made an emerald pit in the darkness, and he would say:

"I wonder."

Then Quickly would begin to wonder, too; Stumbler would hang his big square head and stick out his lower lip, wondering slowly (for Stumbler had some difficulty in making his brain work), while Shy would sit in the stern and blush, for he had no difficulty in making his mind work whatever, especially on such topics, being young and vigorous and very fond of his wife.

Of course they kept watch. They watched the lights of the other fishermen's boats and if one turned homewards earlier than the rest, instead of going to bed next morning they stayed awake, red-eyed and irritable, and they would pester the villagers, until they had found out the reason, which, when they found it, never satisfied them. But even then, there were days when the fish shoals were on the run, and the fishermen had to chase them for an hour or so before they settled round the light. *The Dancing Woman* would show her paces, and take them fast and far away from their companions. And then, when the others were out of sight, who could tell what they were doing? What was there to stop an amorous fisherman—even a boatload of four—creeping back to shore, and nobody the wiser? Besides, not all the villagers fished. Some of the young men were net-menders, a daytime job and very monotonous. If the young net-menders' thoughts were anything like their jokes, what woman could be safe? Net-menders were Quickly's especial worry because one morning, after a shark had got among their tackle during the night, Quickly's wife had said:

"I'll take the nets to the mender's, Quickly. You rest yourself. You look tired."

Quickly's suspicions had been instantly aroused. It was

not a wife's duty to take care of the nets, however solicitous for her husband she might be. He was not a man to dawdle in anything, and he could put two and two together faster than any man. He did, and his peace of mind was destroyed for a month. Stumbler was in a worse case. He could not put two and two together at all, and so he was driven to suspect everybody. Luckyman, who knew how to put things in a breezy manner tried the device of joking with his wife about the cow-herds, men again, with little to occupy their minds during the long hot day. His wife laughed long and heartily and kissing him, dropped the matter and never raised it again —in all as unsatisfactory state of affairs as could well be imagined.

Shy said nothing, but every time his wife raised her eyes in the presence of another man he was immediately sure that they both were laughing at him, for he was convinced that there was not a man in the village who could not make a better show at making love than he.

Such, in the small hours, by the light of the lamp reflected from the water, were the gloomy thoughts, night after night, of the four jealous friends. It was fortunate that *The Dancing Woman* was an intelligent and friendly craft. Otherwise many a time when her owners were sunk in reverie, she would have got herself stuck on a mud flat. She kept them afloat; but she could not keep them fishing, and as the months wore on Luckyman, Stumbler, Quickly, and Shy caught less and less fish and grew more and more certain that someone was sleeping with their respective wives.

Now for many years it had been the custom of the four friends to stop at a temple on their way back from selling their fish and to give the Brahmin who looked after it a tenth part of the money they had made, as a devout offering. They would ask him to pray for success for their next catch, which he always did very heartily. Thinking about this one night at sea, Quickly, who was wondering whether they ought not to give up the practice now that their earnings were growing so small, was suddenly struck with an idea. The next morn-

ing, instead of handing the priest the money, Quickly kissed the hem of his robe and said, "Master, we are simple men but our souls are very troubled. We want you to help us." The Brahmin who had not previously thought about the fishermen's souls—he had, after all, been asked to pray for fish—looked somewhat doubtful.

"I am not at all sure that it is proper for you to have troubled souls," he said, shaking his fat chops at them. "Whatever the bother is, you must submit to the will of the gods. They have planned everything that has ever happened in the Universe and if you four fishermen don't happen to like it, well, that's a sad state of affairs, of course, but I doubt if the gods will alter their plans because of it."

Stumbler and Shy were abashed at this rebuke. Even Luckyman was a little out of countenance. But Quickly, once more kissing the hem of the Brahmin's robe, said:

"Master, we do not want the gods to alter the Universe. We are only humble men, and if the gods have arranged that other men should sleep with our wives, we think that it is fine, but we would just like to know who is doing it."

"Oh?" said the Brahmin. "*Oh!* O—ho—ho—*ho.*" For although he was aware that the things of this coarse and material world are all illusion, he had also discovered—during long hot afternoons spent on his bed flat on his back—that some illusions are more interesting than others: and in the category of interesting ones came the wives of Stumbler, Luckyman, Shy, and Quickly.

"So *that* is what is troubling you," he went on. "Who d'you suspect?—how did you find out?—how long has it been going on?—Does anybody know? Does anybody guess? Is it the same man for all four of your wives? Or a different one for each? When does it happen?—What happens? Well if you're all going to sit there with all eight of your jaws clenched shut and not telling me a single fact you can't expect me to help. Answer me."

"Master," said Luckyman, "we will. But we were waiting for you to stop speaking."

"Well," said the Brahmin, sitting back on his large haunches. "I have stopped. Who d'you think it is?"

"The net-mender," said Quickly.

"The . . . what do you call-him," said Stumbler, as the Brahmin looked at him. The Brahmin clicked his tongue against his teeth impatiently and Luckyman supplied the word.

"That's right. The cow-herd," said Stumbler. "I suspect the cow-herd." Shy, flushing, said he suspected everybody, and Luckyman, seeing that the Brahmin was growing impatient again, said that he thought that the man in his case was the foreign fellow who came round selling wooden bracelets.

"Have you any proof?" asked the Brahmin.

"It's the way my wife talks," said Quickly.

"Eh? Proof?" said Stumbler. "Oh. *Proof.* No. No proof."

Shy said:

"I'm sure it's somebody. I feel it in the pit of my stomach," while Luckyman turned the habits of the bracelet seller over in his jealous mind, and said: "Why should he always come just when the boats set out?"

All four had the feeling, now that they were faced up with the question, that their answers did not amount to very much.

But the Brahmin, it seemed, needed even less proof than they did.

"So you want me to ask the great god Shiva, who knows everything, to reveal the names of these scoundrels?" he said, and when they all nodded, he went on to be most affable and accommodating about the fee. They could pay when it was convenient, but they must promise faithfully to report all their suspicions and of course even the slightest actual fact every day as they passed the temple.

"But," said Quickly, "if the great god Shiva knows everything he'll know all that too."

"If your fish," said the Brahmin rudely, "stink as much as your theology, I quite see that I shall never be paid."

It was true that none of the fishermen knew even the first principles of theology; but they knew one of its leading conclusions, which is that it is a very bad thing to contradict a priest. So they said they were sorry, promised to do what they were asked, and left.

Now in the Rann of Kutch (Valmiki went on) the great god Shiva was held to be one of the most powerful of all the gods. Every day from temples all over the land the god's ears were assailed by millions of prayers and his nose by the smell of seas of clarified butter. He had one additional eye in the middle of his forehead with which from time to time he reduced unfortunate human beings to a heap of ashes. He concerned himself with the potency of the organs of generation, a more amiable characteristic and one which accounted for a good number of the prayers and most of the butter.

He was deeply revered and very popular. The blessings of the other gods, such as wealth and good fortune, were erratic. The blessings of Shiva were children and these came to his worshippers with a frequency that spoke well of the god's concern for his devotees, and, as the priest explained, when they were male children (which everyone wanted) it was clearly the mercy of Shiva at work, and when they were not, it was as clearly due to the wickedness of the worshipper. In this way the god could do no wrong. In any case, he could do no wrong because he was a god and a god cannot do wrong by definition. However any two arguments are better than one, even if neither is a very good one. Great, in any case, was the glory of Shiva and his priests reflected it in their rotund faces which were like copper-coloured moons. No man who had received the favours of Shiva could not be so ungrateful as to leave his priest unfee'd, and no man who wanted them would be so unwise.

Thus the Brahmin in the village of the four jealous fishermen was able to take life easily. It added to his peace of mind that he did not believe that Shiva existed. After a lifetime of praying to the god, preaching about him, and offering him

sacrifices, he had come to the conclusion that Shiva was a great deal of nonsense. Cautiously discussing this with fellow-priests of a similar age he found that they had arrived at the same opinion themselves. But though they all thought Shiva an old wives' tale, they did not find that this hindered them in the discharge of their religious duties. No man can be at his best as a public figure if he feels that at any moment his superior will open an eye and burn him to ashes. "Nobody," as they reasoned—although strictly in private—"lives his life on the supposition that he might at any moment be struck by a thunderbolt. Nor can we. Nor need we. As far as commonsense and a strict attention to the facts can show us, Shiva does not exist."

But he did. Not only did he exist, but he was often in the fishermen's own village; and not only was he often in the village, but he was fond of sitting outside his own temple.

On such occasions his third eye was kept tightly closed and it therefore appeared to be no more than a dignified wrinkle on a brow which was scored with the lines natural to a profound and benign philosopher. This is what Shiva would have passed for, except that his eyes were so bright and lively, and his glance so darting that he had something of the look of a travelling charlatan lying in wait for a dupe. This impression the god increased by wearing the robes of a member of a religious community vowed to poverty. In this way he was able to sit, quite ignored, at the temple gate, save for worshippers who threw him a coin, but who immediately looked away in case (as was the habit of holy mendicants) he should ask for more.

It is Shiva's duty to destroy the earth: he may do it when he pleases and what we call History is merely Shiva's procrastination. He was given this task by Brahma the Creator, a greater god even than Shiva; a somewhat profounder thinker but less sympathetic. Brahma made the world and peopled it with human beings. Having watched the result for several dispassionate millennia, he summoned Shiva (this was about eight hundred years after men had discovered the

wheel) and said, "I can take all this to pieces again but it would be tedious and I am otherwise engaged. Destroy it or preserve it as you please." He then dismissed him with the toppling courtesies that pass between the all-powerful gods on the rare occasions of their meeting, and Shiva, after waiting a polite century before looking at his gift, came down to earth, the first of many visits.

It was his habit to take a turn or two about the world, observing us, and then to seat himself upon a mountain preparatory to raising his third, apocalyptic eyelid. But he would consider us for a moment (no-one knows but it is said that he has spared us eleven times) and say, "I have noted that in the south-eastern corner they have given up eating one another: who knows (save Brahma who is otherwise engaged) they may even rise so high as to give up the habit of burying a living child in the foundations of their houses." So saying, he would quell the fluttering of his eyelashes and wait for another few centuries. Once more he would go here and there and finally seat himself on his mountain. Once more destruction would tremble in the balance of his lucid mind. He would say, "I have observed that in the westernmost areas they no longer found their houses in innocent blood; who knows (save Brahma who may not be disturbed) whether in time they will give up founding their nations in it." And so, here we are today.

Thus it was no coincidence that Shiva sat outside the fishermen's temple, for he was attracted to human folly, and the prayers of the fishermen, reaching his ears even though garbled by the perfunctory Sanscrit of the Brahmin, nevertheless interested him profoundly. Having made it his business to find out the truth, he had discovered that the wife of Luckyman, the wife of Stumbler, the wife of Quickly, and the more newly wedded wife of young Shy were all chaste and all virtuous and all respecters of their husband's beds.

The Brahmin had discovered the same thing, and this is to his credit. His credit lies in the fact that he had less

resources than the god. He could not make himself invisible, or pass through mud walls, or cross-question the village dogs. But he had another instrument. He was known as a man who was scandalised by other people's moral delinquencies. He was rewardingly shockable; his facial expressions of outrage were dramatic and exquisitely apt. He practised them daily. Therefore, every piece of scandal was tried on the Brahmin as a coin is rung on marble. But he had found that hint and fish as he might among the old women and the old men of the village, not a word out of place ever came his way about the wives of his four petitioners. So he concluded that they were faithful.

The Brahmin had sighed and dismissed the matter from his mind. If he was not wholly gratified at this evidence of upright living among his parishioners, it was not from any base motive. He was a man of balanced outlook: he admired the virtue of the women but doubted the enterprise of the young men. But if he could dismiss the matter from his mind he could not get rid of the four jealous husbands from his temple.

They came regularly each morning and as regularly the Brahmin told them that Shiva had not deigned to give an answer. Finally he told them that in his opinion there never would be an answer. Possibly (he said) their wives were virtuous. They came again next day, all four this time as mute as Stumbler, but still determined upon an answer. Positively (the Brahmin said) their wives *were* virtuous. Since the god had not answered, there could be no doubt about it. He bid them goodbye, and told them that they should be happy men.

They were nothing of the sort. They were jealous men; they had distrusted their wives, for months, and few things bind men together in comradeship more than being cuckolds. It is a silent communion, a wordless sympathy, and Luckyman, Stumbler, Quickly, and Shy felt it, every night: and they were not at all happy to think that they were going to lose it.

Again, they had been married for money. Their wives were beautiful but not always interesting; or at least they had not been so before they were suspected. Now every one of their words was anxiously absorbing: none of their gestures was allowed to escape unnoticed; while in the marriage bed, the thought in the minds of the jealous fishermen that they might have been supplanted and—worse—surpassed, urged Luckyman and his three friends on to perform prodigies. This always has its interest for the performer, especially in retrospect. Previously, their usual conversation aboard *The Dancing Woman* had been about the admirable performance of their boat. For all save Shy, this now gave place to the discussion of things in which they could take a more vivid, though not less technical pride. Shy did not take part in these conversations, but from no more shameful reason than his habitual modesty. He agreed with the others that a new interest had been added to their lives and regretted, as much as they, the risk of it being taken away.

Lastly, their jealousy had made them men of importance to themselves and—what with their temple comings and goings, their questions and veiled looks—men of mystery to the rest of the village.

Could it be that all this was built upon their own mistaken fancy? They turned the question over in their minds. Stumbler scratched his head, Luckyman looked gloomy, Shy wrung his fingers, but Quickly gave the answer: no. They went back to the temple and saw the Brahmin. It was a day in which Shiva was sitting outside his shrine, and the god heard their conversation as they came out.

Quickly was saying:

"A silver net! Even if it is only as big as my hand, that will cost a great deal of money."

Stumbler kicked the stones unseeingly as he walked with his companions past the disguised god and muttered:

"A silver man no bigger than . . . what is it . . .?"

"Your thumb," said Luckyman, "that'll be fifteen silver pieces just for the metal. Then what is my bracelet going to

cost, do you think? I'll have all the fiddle-faddle of decoration to pay for and . . ."

" . . . and where shall I *get* a silver phallus?" said Shy. "How can I ask the silversmith to make one?"

"Still," said Quickly, "if it works . . ."

"If the god Shiva is pleased . . ." said Luckyman.

"And he tells us what we want to know," said Shy.

"You mean . . .?" said Stumbler.

"The names of the men who are sleeping with our wives," said Luckyman, nodding.

"And you see," said Quickly, "that priest *does* think there's someone for all he tried to put us off. Testing us, that's what he was doing. Very clever, these priests. Testing us, you see. But all the while he knew there was something in it, or else he wouldn't be putting poor men like us to the expense of these presents to the god, would he?"

"I wonder," said Stumbler, "what he'll do with them?"

"Who?" said Luckyman.

"The Lord Shiva," said Stumbler, and swore as he stubbed his toe.

More the god could not hear, for they were too far away for the human ears which he had assumed when he disguised himself as a holy mendicant.

But he had heard enough to tell him that his priest was up to some rascality. The third eye in his forehead which looked so like a quizzical wrinkle, moved slightly. The bark of a nearby willow shrivelled and gave off smoke.

The god rose. The god entered his own temple. The god greeted his own priest. His own priest waved a careless hand at his own god and went on with his task, which was pouring melted butter over the great stone *lingam*.

"And there's not a word of truth in the whole thing," said the Brahmin when he had explained the case to his visitor. "It is all their imagination. They stare into those fishing lights of theirs and addle their minds."

"Poor fellows," said the god, and in his disguise as a holy

mendicant he found it easy to throw a touch of mockery into his voice. "And now they'll be poorer than ever."

"Ah," said the Brahmin, smiling across his broad face "so you know about the silver votives?"

"Yes," said the god. His third eye moved very slightly thus giving him an expression of worldly cynicism.

"I know what you must be thinking, but how else was I to get rid of them?" asked the Brahmin. "You won't believe me, but I hope, I do actually hope, they will not be such thundering fools as to have them made. But they will. I know it. And I shall have to take them. I see that you smile. Well, I don't blame you. But this is a small place and if I didn't take them I would lose all my influence. Still, simple tricks for small places, big tricks for big ones. . . . I suppose," said the Brahmin, with friendly envy, "that *you've* been to the holy city of Benares."

"I have," said the god.

"I've always wanted to go. Always," said the Brahmin sighing. "Conversation: that is what I miss so painfully here. Perhaps," he said facetiously, "a good long chat will be my heavenly reward."

"The conversation of the gods," said Shiva, "is very sparing."

"Ah, the gods!" said the Brahmin, slowly closing one eye, "the gods are very accommodating when it comes to things that they like. They like . . ."

"Holiness," said Shiva.

"For one thing," the Brahmin amiably agreed. "And for another," he paused, and then reaching under the altar steps (which he could conveniently do because he was sitting on the bottom one) he groped about. "For another," he repeated, bringing out a gleaming brass container by its lid "they like cold boiling fowl spiced with a little cardamon seed." He took off the lid and sniffed the odour of the food inside.

"The great and good god Shiva has a great partiality for boiled fowl offered by devout persons who are also good

cooks, hasn't he?" The Brahmin, winking again, hospitably held out the brass receptacle to his guest.

"Yes," said Shiva, and took a piece of chicken. "This man," he had told himself only a moment before when he had almost determined to destroy him on the spot, "this man is a rascal and does not believe that I exist. But after all, he is better than those others who are rascals and believe that I do." He thus ate the chicken with a tranquil mind, and with a sufficiently human palate to cast a silent blessing on the cook (for ever after her chickens were plump, much to the envy of her neighbours).

When they had finished the chicken, they washed their fingers and gargled their throats at the well behind the temple, spitting out water to the North, the East, the West, and South as ritual prescribed. They then sat in the shade of one of the buttresses and Shiva said:

"Now supposing there were a way of curing these four fishermen of their jealousy, would you use it?"

The Brahmin was picking his teeth.

"Yes, but there isn't."

"You mentioned Benares," said Shiva.

"Ah, Benares," said the Brahmin, and sucked some chicken out of a cary.

"When I was in Benares I was given a powder for use in just such a case as this," said Shiva. "The man who gave it to me is a very famous rishi. You take it with a little water and it enables you to be in two places at once, although you are visible only in one of them. By using it a man can go about his daily work and still be with his wife—unseen, of course, but seeing everything. Since you say that there is nothing to see, your fishermen should soon be cured."

Thus Shiva: and in saying these words he set philosophers a problem, in the solving of which heads may yet be broken and blood still flow. For the gods, by their essence, cannot lie. But Shiva lied. There was no sage in Benares who gave him the powder. There was no magic powder. It was only a little red earth which Shiva had quickly scooped up from

the temple compound while the Brahmin had turned his back to clean his teeth. The god had put it in the small wallet that hung at his waist. Now, opening this leather bag, he showed the Brahmin the dust.

The Brahmin, smiling, shook his broad round head from side to side.

"You forget," he said, "that this is not Benares. It is a little fishing village."

"I do not forget," said Shiva.

The Brahmin ignored him and went on:

"As the guru who taught me the elements of my job always said to anyone who was going to take up a cure of souls in an unknown village, 'My son, the smaller the place the fewer the fools.' "

"That may be a remark showing worldly wisdom," said Shiva, "and it may also show rather more worldly wisdom than is fitting in a holy man, but it has nothing to do with this powder."

"It has everything to do with it," said the Brahmin. "In a little place like this a priest can't afford failures. If I was a priest in Benares or Ayoda and I gave this to some simpleton and—of course—it didn't work—how could it? Ha! . . . well, there would always be hundreds of other fools and temple-haunters to swear for the honour of their priest that it worked very well with a friend of their first cousin some ten years ago. But here—well, as my guru said, there aren't enough fools to go round. I should lose my credit."

"But if it did work, your credit would be increased," said Shiva, "wonderfully increased."

The Brahmin's broad mouth opened in a bellow of laughter. He struck Shiva on his knee.

"And so would yours, my good friend," he said, wiping his eyes, "in all the towns in which you've sold it. But I don't think you'll go back to find out if it has. Ho! ho! ho! That's where you foot-loose fellows have the advantage of us poor fixed priests. Onwards to holiness eh? Never look back, eh? You never know who might be after you with a pitch-fork!"

With which he burst into more loud and friendly laughter. But suddenly he stopped.

"What is that," he said, pointing with a thick finger to the wallet. There was something half buried by the sand.

"I do not know," said Shiva.

The Brahmin prodded the sand and took the object up between his fingers. It was a small beetle of carved stone. The Brahmin held it up and looked covetously at it.

"Do you know what it is?" he said.

Shiva said:

"No. The wallet belonged to a dead member of our order. He passed it to me a few days ago." Thus simply did the god describe the miracle he had performed taking on the human form, the dress, and the wallet of a man who had fallen dead a moment before he did so.

"It's from Egypt," said the Brahmin. "It's a great bringer of good luck. A priest I knew had one and he discovered buried treasure."

"You believe in this Egyptian fable?" asked Shiva.

"I do and I don't. Well, then, yes I do."

"Would you like it?"

"Yes. Yes indeed," said the Brahmin, his eyes glittering.

"Would it not, do you think, be better to pray to the great god Shiva for anything that you may want? You are his priest."

The Brahmin grinned and shrugged his shoulders.

"You should know the answer to that," he said.

The great god paused. He thought of the millions of prayers that he ignored daily. A god is nothing if not magnanimous.

"I grant you your point," he said. "I shall give you this if you will do one thing."

The Brahmin closed his large hand over the amulet.

"Yes, yes. What?"

"Give the powder to the fishermen. Tell them what it is for and tell them that they must put as much as they can hold between finger and thumb in a jar of water and drink the water fasting."

"Is it a drug?"

"No more a drug," said Shiva, " than the common earth that is beneath our feet."

"Well, if you'll indulge my fancy, I'll indulge yours," said the Brahmin, opening his hand and gazing at the scarab.

"And now," said Shiva, "I must go."

"Onwards," said the Brahmin, "to holi . . ." but when he looked up from his amulet to wink, the god had gone.

XI

The Tale continued

THE next night four silent fishermen launched *The Dancing Woman*, silently lit the lamp, laid nets without a word, and sat down upon the thwarts to await the miracle.

Quickly was the first to break the silence.

"Is everybody here?" he said.

Luckyman looked at Stumbler, Stumbler at Shy, Shy at Quickly and then each checked the others.

"Yes."

"Yes."

"Yes."

"Well, then," said Quickly in a whisper, "is anybody anywhere else?"

None of the three dared answer, in such awe were they of the magic powder, but by the light of the lamp Quickly could see them slowly shake their heads.

"Nor me," he said, and sighed.

Then after a silence:

"You all took it the right way," he asked, anxiously, "and drank every drop?"

"Every drop," said Luckyman.

But Stumbler, lifting his heavy face, said:

"Drop of what?"

"Water," said Quickly. "The water you had to put the powder in."

"Oh," said Stumbler. He groaned. "Did the priest say water? I forgot."

"Forgot?" said the other three in horror.

"I sprinkled it on my curry and rice," said Stumbler. "I wonder what'll happen to me now?" he added, miserably.

"You won't be in the place you want to be," said Quickly,

in a threatening whisper. "You'll be in some deep, deep hole, miles underground with devils pricking your bottom and serve you right for being a silly . . ."

"Sh!" said Luckyman. He held up his hand. The light from the brazier at the prow lit up one side of his brown figure and his handsome face.

"She's going to bed," said Luckyman. "She's loosening her hair. She's yawning."

Then the other three knew that it had happened to Luckyman first.

"Is she alone?" whispered Quickly. The sea was quiet and there was no noise save the tapping of the water on the side of *The Dancing Woman*, as he waited for the answer.

"Quite alone," said Luckyman, at last.

"Can you touch her?" said Stumbler.

There was another pause. Luckyman made no move except that he allowed his raised hand slowly to fall to his knee.

"I touched her," he said. "She felt it. But she brushed at her shoulder as though it was a fly."

"I can hardly believe it," said Quickly. "It seems such an impossible thing to . . ." His voice faded. Then in a different tone he said, "So that's where she hides the money she saves."

Then for a quarter of an hour neither Luckyman nor Quickly spoke. They would not answer Stumbler's questions. But from their eyes, their changing expressions, their little smiles and frowns, he knew that they were in *The Dancing Woman* but also at home with their wives.

"Has anything happened to you?" asked Shy, at last.

"Nothing," said Stumbler. "Except I think I'm getting a stomach ache. What about you?"

"Me?" said Shy. "No. But, to tell the truth—it sounds foolish I know but . . ."

"So she drinks," said Stumbler, suddenly, in a mutter: and then, "I can't blame her. It can't be an easy life, living with me."

"Is she alone?" asked Shy. But Stumbler did not answer. Like the other two, he sat abstracted and silent on the thwarts of *The Dancing Woman*, there in the boat with Shy and yet not there at all.

Shy got up. He mended the fire, he eased the fishing tackle, he coiled a rope and he cursed himself for a fool. He alone of the four had not taken the powder. He had gone off by himself to put it in the jar of water, but then, thinking of peering unseen at his young wife, maybe in bed with her lover, he was overcome with embarrassment, and, hiding the powder in a tree, he had joined his braver companions on the beach.

But when the night's fishing had been done (after a fashion) and they were selling their catch to the merchant, Shy was glad that he had not taken the powder. His companions were all so abstracted, they all took so little interest in the bargaining, that the merchant straightway halved his usual price, complaining of a glut on the market. When the merchant named his figure Luckyman looked at him benignly and smiled a slow smile of pure pleasure. The merchant breathed heavily through his nose and plainly told himself he could have got away with a crueller price.

"They're right; I *am* a lucky man," said the smiling fisherman. He was seeing how the morning sun, falling on his wife's pillow, brought out all her beauty as she peacefully slept with her cheek upon her arm.

"You are," said the merchant. "And of course, I'm not going to take all the fish at that price. Only the big ones. For the little one's I can't go further than . . ."

He paused. He considered. He named the price and young Shy lost his temper. He lost it so thoroughly that for the first time in his life he spoke up for himself.

He attacked the merchant in a torrent of words. The merchant recoiled. The merchant waved his hands in a vain effort to calm him. Shy squeaked with rage. The merchant raised the price a rupee. Shy advanced upon him with a threatening gesture, and the merchant fell on his knees

raising, as he did so, the price by two rupees. Shy stood over him and dictated his own terms. As the merchant said afterwards, it was like being attacked by an abusive, swearing, red-eyed rabbit.

Luckyman, Stumbler, and Quickly observed all this with as much detachment as the market-policemen who had been well-bribed by the merchants to stay out of market-day quarrels.

When the merchant had paid and the money had been divided—the uninterested manner in which the bewitched three took their shining coins would have been a lesson to a saint—the four friends set out across the mud-flats for home.

Shy was full of his victory. He went over his argument with the merchant step by step, greatly improving his phrases, stopping every so often for his friends' applause. But all Luckyman said was:

"You made so much noise I was afraid she'd hear and wake up. I didn't want her to do that. She looked so pretty. But of course you were two miles away."

All that Quickly would say was:

"I heard her murmur, 'I'll be late with Tu-Tu's breakfast.' At least I think she said Tu-Tu. That's what she calls me, you know. But just then you bawled something very rude at that man and I couldn't quite . . ."

All that Stumbler said was:

"She snores."

For a brief time of triumph, while they had been dividing up the money, poor Shy had thought of appointing himself the manager of their partnership. He had thought of declaring:

"Fellows, you go on watching your wives. Leave all the business to me. What do you say?"

But now that moment was past. As he walked along the road by the side of his distant-eyed and silent companions, ignored by them or, worse, considered a nuisance when he spoke, he felt lonely, forlorn, and out of the running. When

Quickly, turning his eyes away from the horizon for a moment, asked him:

"You don't say anything about your own wife. Is everything all right?" Shy said, "It will be," and he left his friends at the entrance to the village, and went secretly to the tree in which he had put the powder.

It was still there. He tucked the packet into his loincloth and went home. Looking at his wife as she bent over the fire he thought once again how embarrassing it would be if he had to watch her in bed with her lover. He said:

"Rani, I want you to remember that whatever happens it is because I love you."

"Yes, yes," said Rani. "Eat your breakfast."

That evening, before he set out to join his friends for the night's fishing, he took the powder. When he met his companions he explained to them how the night before he did not have the benefit of the powder, and how, this night, he had taken it. They said they were glad that he had changed his mind. But they were soon to be very sorry.

That night Shy was the first to go home to his wife in spirit. They had just laid the nets in a circle, and Shy was looking down the black side of *The Dancing Woman*. He was watching the light from the lamp caper and shiver in the water, when the change began.

It started with the sounds of things. At night, the small noises of the boat—the straining tackle, the footfalls on the planks—were always echoing as though the sea were hollow. Shy was fond of this vastness behind the noises and he missed it if he stayed long ashore. The first thing that happened now was that a box seemed to close about his ears. The vastness went, the hollow sounds gave way to the padded sounds of dry land. Then a flicker of light on the water below him stood still and became a brass cooking pot. He recognised the cooking pot as one that his wife always kept on the floor near her fireplace. Next, he saw

the fireplace, then the wall on either side of it, then four walls, and he was home.

The fourth wall of the room was not of smoothed-down clay like the other three. It was a curtain of strong cloth, once white but grey now with the smoke from charcoal fires, and across it danced angular figures of men and women, in rough imitation of a village dance. His wife had made them and sewn them on to the curtain in the first few months of their setting up house. He had boasted round the village that he had married a beauty and a houseproud woman at the same time—a rare thing, as everybody said. But as the marriage wore on, she relied more and more on her charms to please her husband and less on her sense of art. Her choice was wise and pleased her husband; a curtain is only a curtain, but in a woman there is infinite variety. Yet her husband, in his more elevated moments, was still fond of the curtain. He looked at it now, recalling the happiness of their earlier first love. He had only to lift it, pass into the bedroom, to see if that love had been betrayed.

He hesitated. He remembered a game he had played as a child to settle prettier problems. He told over the figures, saying as he did so:

"I *am* a cuckold. No, I'm *not*. I *am* a cuckold. No, I'm not. I *am* a cuckold," and so on. But from the tail of his eye he sensed an ominous deficiency of figures. Like most shy men he was not, in the final test, a coward. He lifted the curtain.

Rani lay chaste and sleeping, their baby in her arms.

Just then there was a noise from the house next door, which belonged to Stumbler. Rani woke. Her great soft eyes looked straight at her husband. Seeing her thus, gracefully lying in the bed and looking at him, Shy was seized with desire. He thought passionately of taking her in his arms. He knew from the others that she would feel his touch, but he wondered, since he was invisible, whether she would altogether know what to make of it. While he hesitated, he heard voices in the next house. He listened,

and Rani listened. Then Rani sank back into sleep, and Shy listened alone.

When Stumbler had moved in spirit from *The Dancing Woman* to his house, he was greeted by no shining pots or artistic curtains. There was not one child but eight. They fed in a circle sitting on mats on the floor. When they had done, it was his wife's custom to collect the metal platters and make a heap of them by the door-post, a convenient place from which to take them to the well to be scoured and brought back, gleaming, to the house. Each time she made the pile, she saw them clean and bright, as they soon would be, and proudly ranged along the mud wall as they were in other women's houses. But other women did not have eight children, nor Stumbler, nor an exhausted feeling which had to be removed with sips of the fermented sap of the palm tree. So each day the platters stayed by the door and here Stumbler, returning home in the spirit, fell over them.

The noise woke the youngest child and an intelligent boy of eight. The baby yelled ferociously, awakening (as we have seen) the neighbour, but not its mother. This was the duty of the boy of eight, who pulled her hair and slapped her cheeks until she, groaning, sat up. When she heard the baby's squeals she rose, pushed the hair from her face, and took the baby in her arms.

"Drunk or sober," said Stumbler to himself, "she's a good mother."

The intelligent boy lit the lamp. His mother sat on the floor and nursed the baby, pushing a sweetmeat into its mouth as frequently as it spat it out. Stumbler, pressed against the wall, saw all this with a father's pride. The baby, during those moments when it could free its mouth, was making a sound which (it had been agreed between husband and wife) meant that it wanted Stumbler.

"Why isn't Dada home any nights?" asked the boy of eight.

"Because he is a fisherman," said the boy's mother. "And

if he didn't go out at night there'd be no money to buy you food."

"Why does he go to sleep in the daytime when he comes home?" the boy next asked.

"Because he is very tired," said his mother. "Fishing is very hard work."

"Will he always work?"

"No. One day he will give it up and be at home all night."

"When?"

"Before he trips over something and falls in the sea and gets himself drowned," said his mother, "let us hope."

"When I grow up, shall I be a fisherman?" asked the boy, and Stumbler's eyes filled with fond tears.

"If you grow up to be as big a fool as your father," said the boy's mother, "I suppose you'll have to be."

In the still Indian night these words could be plainly heard by Shy and they brought his mind back to *The Dancing Woman.* He immediately found himself there. Seeing that the nets were straining their ropes, he called the attention of Quickly to them and together the four hauled in an early and enormous catch. For an hour, while the fish cascaded from the nets like wriggling pieces of metal, he did not think of his wife. Then he rested and mopped his forehead. He once more thought of Rani and on the instant was standing outside his house. He did not go in, but deliberately bringing his mind back to the remarkable catch of fish, he found himself, as he suspected that he would, back both in spirit and in body on *The Dancing Woman.*

While the four friends cleaned the nets of fish which had fixed themselves so firmly that they could not be shaken out, he explained his discovery of the way in which the powder worked. From their short grunts in reply he learned that they too had come upon the secret. For the rest of the night all four agreed to keep their minds off women and upon fish, for such a catch had not been known in these waters for twenty years. In their hearts they thanked the great god Shiva for thus making up their losses and the

god, who was particularly listening to these four of his devotees, heard. In reply, he put it into their hearts to make an offering that coming morning at his temple.

They were in magnificent fettle with the merchant. No longer distracted by being in two places at once, they drove him to offer a fair price: and the envious looks of the other fishermen told the merchant that there would be no glut. He bought, and he paid, and he paid so much that Luckyman, Stumbler, Quickly, and Shy had to take off their turbans to make a bag to hold the money.

As they walked away each one said with great earnestness to the others that they should make an offering to the Brahmin: not only for his wonderful kindness in giving them the powder—and here they all clicked their teeth in astonishment at its properties—but also in acknowledgement of the god's new favours.

With the look of devoted and determined men, they marched up to the temple. The Brahmin, seeing them coming, cursed the mendicant and his powder, and tucking up his robes, he fled round the back of the temple into a nearby clump of tamarind trees to weather out what he feared would be the inevitable storm of disappointed protest. He wished that he had restrained himself from making a charge for the powder and promised himself that he would return the money. He was greatly surprised to find on returning to the sanctuary when the coast was clear, four neat little piles of silver rupees laid out on the altar's lowest step.

Meanwhile the four fishermen made their way home in the best of spirits, filled with that most delectable of sentiments, the sense of having done a virtuous thing without particularly feeling the expense. In this happy mood Luckyman and Shy fell to the pleasant task of comparing the beauties of their respective wives when seen, by an invisible husband, as they lay sleeping.

Shy kept the conversation within modest bounds, but not so Luckyman. He drew such a picture of his wife that, as they came within sight of their homes, Shy's imagination

was inflamed. On entering the house and being greeted by his Rani, Shy was not as overwhelmed by her beauty as was his custom. She seemed, he thought, a little dull in her looks. He asked her if she felt unwell, but she, with surprise said:

"No, no, not in the least. Eat your breakfast."

From breakfast to their day bed, from day bed to supper-time, from the supper-time kiss and *The Dancing Woman* to watching Rani asleep again as he stood invisible by the curtain seemed for Shy a matter of a passing hour, his thoughts were so alluringly disturbed.

Even when he looked at Rani his thoughts wandered elsewhere—and so, of course, did his invisible body: such was the nature of the powder.

He found himself, that is to say, in Luckyman's bedroom, looking down at Luckyman's sleeping wife.

Luckyman had been pointed when he had described his wife and he had told the truth. Young Shy had seen few women save his wife for more than a few moments. Fishermen's manners did not allow staring at girls, and to stare at another man's wife as Shy was doing now would have been cause for complaint to the village headman and a fine. Shy gazed, secure and enraptured.

Then he cautiously looked round the room to see if Luckyman were present. Remembering that he would not see him if he were (would Luckyman see *him*? who knew? the powder was unpredictable) he even more cautiously thought of fish. As quick as his thought he was back in the boat. He noted with satisfaction that there was trouble with the tackle, and that Luckyman was bent over it with every appearance of being there and nowhere else. Languorously allowing his thoughts to slide, Shy transferred himself to Luckyman's bedroom.

Luckyman's wife was called Silvermoon and she was a great dreamer of dreams. She had made something of a study of them, and she knew by heart some hundreds of rhymed jingles which helped in their interpretation. Silvermoon would even dream for other people: they had merely

to give her something to hold in her hand which belonged to them and she would dream dreams symbolic of their future.

But that night Silvermoon had no need of jingles to interpret her strangest of strange dreams, and she was not, she felt sure, dreaming it on behalf of anybody else. The words whispered so passionately in her ear were meant for her alone; the invisible caresses were far from symbolic; and unlike her other dreams, it went on, deliciously, even when she had woken up. When it was over and she was alone again, she lay in bed, pondering. She was puzzled but not utterly at sea. Her visitor, she reflected (but in her own simple words), though lacking all flesh, was still plainly subject to its promptings.

As for Shy he fled the house both elated and alarmed. His elation was only to be expected: his alarm was due to his peculiar circumstances. A lover must be prepared for a husband returning unexpectedly: there are windows, cupboards and backdoors to help him. But there are no aids for a lover who must guard against a husband returning invisibly. For all Shy knew, Luckyman might have been in the room. But then (Shy reflected as he focussed his corporeal eyes on the details of *The Dancing Woman*) if he had been, for all *he* would know, his wife might have been having nothing more than a restless night. This, Shy decided was the husband's problem. He was glad to find him still intent upon the trouble with the nets.

In fact the trouble with the nets had been such that Luckyman had been unable, all night, to summon up sufficient interest in his wife to get himself away. Stumbler had paid a fleeting and preoccupied visit home; Quickly had made a swift inspection. They were not less in love with their wives; but to a fisherman, when his net is entangled, nothing is more irrelevant than a woman.

The trouble was mastered just about dawn, and there being no fish worth selling, Luckyman went straight home. He greeted Silvermoon and as usual asked her if she had had a good night. As usual she said that she had. She went on to

say (and this was also customary) that she had dreamed the strangest dream.

Luckyman yawned. "Ya—ooo—ho—hum—what was it?" he asked. The question was as formal as it was polite; from long experience he knew that she would tell him, invited or not.

But she hesitated. She blushed.

Luckyman observed her blush. He put down the morsel of food that he was carrying to his mouth without tasting it. He repeated this question, this time without a yawn.

Silvermoon still hesitated, for she felt—she did not know why—that this was a dream that it would be wiser to leave untold. But when her husband pressed the question a third time, habit was too much for her, and she said:

"A prince came and made love to me."

"A prince? How did you know he was a prince?"

"His skin was like silk," she said, "and . . . and . . ." her usual flow of description was stemmed, "and . . . well, his skin was like silk."

"What did he look like?" asked Luckyman, suspiciously.

"I don't know," said Silvermoon. "I didn't see him."

"You mean you couldn't see him because it was dark?" said Luckyman.

"It wasn't as dark as that—in my dream I mean. He was—well, it was all a dream of course—but he was—you couldn't see him."

"You mean he was like air?" Luckyman waved his hand in demonstration.

"That's right."

"Oh."

"Don't look so angry. It was only a dream," said Silvermoon, distressed by the cloud which had settled on her husband's face.

"Oh," he said again. "A dream, was it?" He lifted some food to his mouth and put it down once more without it reaching his lips. But so deep in thought was he that he chewed on nothing for a while.

"Listen," he said, "say nothing about this to anyone. D'you understand? Nothing."

Silvermoon nodded, her eyes wide. An hour later when Luckyman was lying sleepless on his bed she was at the well. The other women, noticing her unusual silence, pressed her to talk. She refused. They pressed again. Fatally, she said:

"I have had a dream which my husband has forbidden me to tell to anyone."

By the time that the sun was in the zenith the whole village knew that Luckyman's wife had been visited by an invisible stranger with charms so extraordinary (including a skin like silk) that it was plain that he was either a god or a very handsome devil.

XII

The Tale of the Jealous Fishermen concluded

THAT night *The Dancing Woman* was wrecked.

There was a bad omen of it in the evening. As Stumbler was leaving his house to go down to the beach, his wife who had been incapable or unwilling to speak to him all day, pushed back her hair from her face, and said:

"Have you heard the gossip?"

Stumbler said he had not.

"Silvermoon's dreamed she has a prince who makes love to her, only you can't see him."

Stumbler said he didn't understand. His wife ignored this remark, as one ignores a familiar mole on the face of one's husband or wife.

"I don't suppose I shall dream anything like that," she went on, "I shall just dream mv usual dream about you."

"What is that?" said Stumbler fondly.

"You have fallen overboard and you are drowning and I am shouting on the bank, 'Swim!' because you are within ten feet of dry land. You keep shouting, 'What?' Then you drown."

"You shouldn't talk like that," said Stumbler. "It'll bring bad luck."

So it turned out. There was a light breeze blowing as they launched their boat, but the night was very dark. Stumbler, made gloomy by his wife's parting words, foretold bad weather. But the others brushed his fears aside. They seemed very preoccupied, each with his own thoughts, and Stumbler feared that it would be a night when little attention would be paid to fishing. Fo. himself, now that his fears

for his wife's chastity had been set at rest, he had little interest left in women. Looking round at his absorbed companions he envied their young manhood.

They raised the lateen sail and *The Dancing Woman* jumped away in a fashion which Stumbler, at the tiller, felt to be a little too lively. The others noticed nothing. Luckyman and Quickly were seated amidships. Shy was up at the prow dismantling the fire basket (for with a breeze blowing it would be no use) and fitting some other tackle.

Quickly said to Luckyman:

"Strange story, that about your wife's dream."

"Women's nonsense," said Luckyman. "I told her not to tell anyone."

"Lover who can't be seen," said Quickly. "Sounds very like . . ."

But Shy interrupted him, turning back and speaking with a new boldness.

"I've often wondered," he said, "but you know that I kept that packet of powder overnight in a tree. Well, suppose . . . that's what I say to myself—suppose somebody had found it, and stolen some, thinking it was a medicine or—well you know what I mean."

"It's possible," said Quickly. "No way of finding out. A lover you can't see, eh? That's a lover you can't catch, it seems to me."

"Yes," said Shy decidedly, and turned back to his work.

Luckyman stared at Shy's back for a long moment.

"Skin of silk," he said, and spat on the floorboards.

Nothing more was said aboard the boat for the next hour. The breeze was too fresh for them to do anything but put on the big cone-shaped trawl net. This was soon done, and the fishermen chose their favourite positions in the boat to wait for the net to fill. By the light of the oil-lamp that hung from the mast, Stumbler saw each of his companions fall into the abstracted and languid state that marked their spiritual departure to their wives. Stumbler shook his head

and sighed. *The Dancing Woman*, it seemed to him, did the same in sympathy. The wind grew colder against his cheek. Stumbler tightened his hand on the tiller and began to form a sentence in his head that would make his companions aware of the danger that Stumbler felt in the air, under his hands and in his seaman's bones.

Five minutes later the gale struck them. It was the rim of a cyclone. The tiller jarred in Stumbler's hand as though it were grinding against rock: the lateen sail shook itself free of its ropes and streamed out before the wind like a banner: *The Dancing Woman* turned a drunken pirouette.

She was beyond Stumbler's managing. He could sail out a monsoon storm but this wind was a sea-terror that was new to him. He called desperately to Quickly to come and take the tiller. Quickly had sailed the Persian Gulf; Quickly had once sailed a dhow; Quickly could master *The Dancing Woman* now if anyone could; but Quickly sat on the thwarts, his head rolling with the boat, smiling vacantly into the storm as if into the face of a woman.

So with Luckyman and Shy. Stumbler, raising his voice above the wind, made them hear him; they rolled love-sick eyes at him and did not move. Then the tiller won its struggle with Stumbler's wrist: it broke free and wave after wave of foam-topped water came eagerly aboard. Stumbler called to his companions again and again but now he could not even see their looks, for the lantern was gone and there was no light from the sky: soon there was no sky at all, but only flying water.

With this peril as a goad, Stumbler rose above himself: he strove, he wrestled, he sweated, he beat his skull and at last he managed to force his reluctant mind to think. He knew that if his companions could be made truly aware of the danger in which the boat stood (for now they moved about their tasks like men of lead, too slowly and too late) they would give up their dalliances, leave their wives in spirit as well as in body, and save themselves. But how could this be done? Shouting and shaking, even blows, were

useless. Stumbler, drenched and dismayed, suddenly saw that he must go to their houses and, invisible appealing to the invisible, recall them.

He fixed his mind on his wife. Her charms were not easy to visualise, although he loved her, and in a running sea whipped by a gale, her allure had never been less. Obstinately, his mind and his body both stayed in the boat. He whispered her name—the same result. He thought of her when young—he had forgotten what she looked like. Half choked with salt water, he imagined her dead to excite his emotions—his grief was inadequate to shift him an inch. Desperately he began to shout coarse words into the wind and people the howling darkness with images of gross delights that they had known together but were never mentioned between them. At last, thanking the gods that his wife was no lady, Stumbler heard the wind die and its sound give way to his wife's snores. He threw her the hastiest of glances as she lay surrounded by her children and, invisible and dry, he sped away to Quickly's house.

He entered the bedroom. A single light burned in an alcove in the mud wall, flickering in the wind which had already begun to blow over the village heralding the approach of the storm that raged out at sea.

"Quickly," he whispered.

There was no reply. But Quickly's wife laughed softly and whispered and the coverlet of her bed humped itself in a manner for which she alone, a slim woman, could not possibly be responsible.

Stumbler went to the bed and seized where he judged Quickly's shoulder to be.

"Get up," he whispered. "It's me."

Quickly's wife giggled again.

"Go away," replied a male whisper from the bed. "Go away, you old fool."

"Not till you come with me, Quickly," said Stumbler.

"What's that you say, you wicked man," said Quickly's wife tenderly.

"The boat's going down. You've got to save it," said Stumbler, shaking the coverlet furiously.

"Get Quickly," said the man underneath it.

"Aren't you Quickly?" said Stumbler, forgetting to whisper in his surprise.

"What is it?" said Quickly's wife sharply. "What is going on in my bed?" and the voice under the coverlet, answering Stumbler's question, said shakingly:

"No, I'm Shy."

"Then what are you doing in Quickly's bed?" shouted Stumbler.

"Well, what Quickly does," said the coverlet, falling back. "Anyway, don't shout so much; I'm getting up." But the last part of this statement was drowned by the loud screaming of Quickly's wife, her sense of propriety, at last, outraged.

"She'll wake the neighbours," said Shy, and then consoled himself with the reflection that even if the neighbours came he could not be seen. At which the woman, as though able not only to hear his voice but also read his thoughts, put words to her screaming:

"Help, help, help! Shy is trying to . . ."

Shy clapped his hand over her mouth.

"Quick!" he said to Stumbler. "Into the street."

Once there, they paused for a moment to gather their wits. The woman calling tearfully upon her absent husband's name, evidence not only of her peril but of her faithfulness.

"But where *is* Quickly," said Stumbler.

"I don't know," said Shy. "He wasn't there when I went in. I scouted around with my hands out."

At that moment the storm struck its first real blow at the village. A great gust of wind swept through the streets, and with it came the thatch of the house which stood next to Shy's.

"Is it a bad storm out there?" Shy shouted to Stumbler, and Stumbler nodded, forgetting that he was as invisible as the tearing wind.

"What did you say?" Shy shouted again, and Stumbler said at the top of his voice:

"It's the worst I've ever seen. We *must* find Quickly."

The wind struck again and shook the roof of Shy's home.

"Rani!" he yelled. "I must warn her."

He began to run, but it was unnecessary. No sooner had he thought of his wife, than he stood beside her bed.

The little lamp fluttered in the breeze and gave too fitful a light for him to see anything clearly.

"Rani!" he said. "There's a terrible storm blowing. Get up and go to the headman's house. It'll be safer because he's got a roof."

"Now you sound just like my husband," said Rani from the shadows. "He always worries so. Don't go yet, Your Royal Highness."

"Who's there?" demanded Shy, his voice rising.

A hand came from the bed. It felt Shy's calf.

"A skin," said a masculine and derisive voice, "like silk."

"What is the meaning of this," shouted Shy, his voice breaking into a boyish treble. "Luckyman! come out of my wife's bed!'

"The meaning is," said the voice of Luckyman, "that you and me is *quits*."

Rani wailed; the wind howled; and the invisible Shy swore in a fashion that surprised himself. Above the din came the voice of Stumbler:

"If you'd only all be quiet I could tell you where Quickly is. I've nearly worked it out but my brain won't go any more. Shy was with Quickly's wife—weren't you, Shy?—and here's Luckyman with yours—and mine's sleeping alone, the gods bless her, so Quickly must be . . . Oh, dear, it's gone again."

"Silvermoon!" roared Luckyman, and the thought of her striking all three at once, they were instantly in her bedroom.

The lamp was in a horn case. It burned steadily. They could see the coverlet over Silvermoon heave desperately.

"But I *must* go," said Quickly's voice protestingly. "Can't

you hear the gale? I must go back to *The Dan* . . . My dear, I tell you I must go."

"Oh," said Silvermoon, embracing the top edge of the coverlet, "so soon? What does a little wind matter? We're quite safe and warm here. My other prince stayed much longer."

"I know, my dearest," pleaded the unseen Quickly. "But perhaps he wasn't a sailor prince. I am, you see, so I must . . . I must get back to my ship."

"You must," said Stumbler, "she's sinking."

"And by the gods," said Luckyman to the coverlet, "may you go down with her."

Thus at last, all four thinking of *The Dancing Woman*, they found themselves back aboard her.

Quickly seized the tiller. The others, knocked down continually by the incoming waves, said their prayers. Quickly tried to get her head round into the wind, but it was too late. With a great leap and a shudder that made the fishermen's teeth rattle in their heads, she went ashore on a bank of mud and lay broadside to the sea and wind.

Thus the four friends were high, but by no means dry, for the next six hours, when, the gale having blown itself out, they were rescued after heroic risks, by one of the fishermen they had jealously suspected of seducing their wives.

One day some four weeks later, Luckyman, Stumbler, Quickly, and Shy were going sadly towards the temple, each carrying a small bundle wrapped in a piece of cloth, when they met a holy man belonging to one of the mendicant orders. He looked venerable, and his forehead was heavily scored with lines made by deep thinking.

"Where are you going, my children?" said the great god Shiva.

"To the temple," said Quickly, and all four bowed to the holy man.

"What are you carrying?" asked Shiva, and they showed him a small silver net, a small silver bracelet, a small silver model of a man, and a silver phallus.

"We are all very unfortunate men," said Quickly. "We were favoured by the great god Shiva but we forgot to make him the presents he asked for. So we lost our boat, and we must build another one, some day."

"Some day," echoed Luckyman, dolefully.

"But when?" said Shy, while Stumbler groaned in misery.

"We have spent the last of our savings on these gifts," said Quickly. "We thought that it was our duty. May the great god smile on them."

The great god did.

"You are good people," he said, "and I think that you have a certain powder that makes you invisible."

All four hung their heads.

"Master," said Quickly, "the Brahmin has told you. Yes, we have."

"Then take back your gifts to your homes and sell them. The great god is satisfied with your willingness to make so great a sacrifice. Then go to the temple, tell the Brahmin of your adventures and give him all that remains of the powder. Do this, and I promise that you will prosper. Now I, who am a devotee of the great god, have a message from the god himself for you. Go down on your knees."

They obeyed, for the holy man spoke with awesome authority.

"When," he said, "in your new boat, you think of your wives on shore, you shall always say these words aloud to one another."

With that the great god went to each of them and whispered in their ears.

Then he dismissed them, with a blessing.

That afternoon the great god Shiva rose to his full height of seventy-five feet, frightening the animals of the village who alone could see him in his giant splendour. He looked at the temple and saw through its walls as through glass. He looked at the Brahmin who was standing alone before the altar, the powder in his right hand, and Shiva saw through

the priest as through still water. He looked at the Brahmin's soul and there he met an obstinate opacity, for Shiva, though a great god, was not Brahma Himself.

The Brahmin spoke to himself and the god heard him.

"How convinçing they were with their story," the Brahmin mused. "Suppose it were true, after all. I would just take a little of this powder—in water, they said—and then Rani and Silvermoon would have another prince to bring them jöy." He licked his lips. The god listened intently. He heard the Brahmin chuckle. The god's eye quivered. The butter on the stone lingam on the altar began gently to smoke. Then he heard the Brahmin snort.

"But nonsense, *nonsense*. What am I saying? It's all part of the game and if I start believing in my own hocus-pocus, why, I shall lose my self-respect."

With that he left the temple and threw the earth contemptuously on the ground beside the well, from where it had originally come. He then returned and, with a sceptical smile, began to intone the first of the evening prayers.

The great god retired to his mountain to think the matter out. But the more he considered the human soul—and particularly the Brahmin's—the more, in a godlike fashion, he grew confused. At last he gave the problem up.

"It is too deep for me," he said. "Brahma alone knows. It is a pity that He may not be disturbed."

So, during the long nights when the new *Dancing Woman* was out at sea and the four fishermen would start thinking of their wives on shore, one of them (and it was nearly always Stumbler) would say:

"Friends, remember the message."

Then the four men would repeat devoutly to one another: "*What is the use of being jealous? A wife is a woman; a woman is a woman; and a man cannot be in two places at once.*"

But Luckyman, Quickly, and young Shy would think for a moment of the time when they could.

Then they would all get on with their fishing, in a tranquil frame of mind.

BOOK III

The Siege of Lanka

I

A handbook for Recruits

THE war between the allies of Rama and the King of Lanka is one of the most famous in the history of India. Most of the leading generals on both sides won striking victories and those that did not employed scribes to write their reminiscences, which were even more strikingly victorious.

Hostilities began in November. The first move was an exchange of ambassadors. Both embassies declared that they abhorred war and wished for a just peace. The ambassadors of Rama described a just peace as consisting in the return of Sita to her rightful husband, the execution by plunging into molten lead of Ravan, the demolition of one-third of the houses of Lanka, the razing of its walls, the imposition of a tax of one-half of the income of all the inhabitants for twenty years, and the life imprisonment of all the Lankastrian generals.

These terms were rejected by all concerned but with special vehemence by the generals, some of whom privately informed the allied ambassadors that while they could see reason in most of the demands they considered that the last clause spoiled the whole affair. Ravan, in the name of his cheering people, denounced the offer as evidence of the barbarity and inhumanity of the enemy. He in his turn proposed, as a lover of peace and in the name of his people (who this time shook their heads at his moderation), that a ten-year truce be proclaimed on condition that Rama gave his free consent to Sita's divorce and re-marriage to him, Ravan, after which Rama was to be torn to pieces by wild horses as an enemy of humanity: further the allied army was to return to their homes, leaving their weapons behind them; an indemnity equivalent to three times the cost of the

war so far to Lanka was to be paid by the principal allies; all officers over the rank of sergeant-major were to do three years' forced labour in Lanka, and all generals were to be imprisoned for life.

These terms were indignantly rejected by the allies as evidence of the Lankastrians barbarity and inhumanity. The ambassadors on both sides returned. Rama's ambassadors, who had been led blindfold through the streets of Lanka and locked in an inner room during all the negotiations, informed him that the inside face of the walls of Lanka were crumbling, and certain elements of the army were ready to mutiny because of arrears of pay. Their report greatly heartened the troops and they were decorated for loyal service to the Allied cause. The ambassadors of Ravan who had been taken to a sealed tent in palanquins with boards nailed to the sides instead of curtains, reported that Rama had already quarrelled with two of the four principal rajas who were assisting him, one of the generals was permanently drunk, and several consignments of arms had proved to be boxes filled with old scrap iron and stones. Their reports greatly strengthened the belief of the Lankastrians that it would be a quick victory.

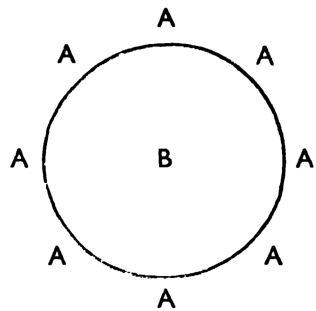
At the end of the war it was found that the reports of both embassies were substantially true. This was not extraordinary. While they were not magicians able to see through a blindfold, on the other hand they were old soldiers, who had been to the wars before.

Both sides now instructed their General Staffs to draw up a plan of campaign.

The General Staff of Rama and his allies met for several days on end in a tent pitched in a location remote from the lines. It was heavily guarded to prevent the escape of secrets. A local milkmaid, gathering succulent weeds to feed her cow, contrived (none knew how) to gather them within three feet of the tent. She was arrested together with her whole family and (through a fault in transmission of orders)

the cow. She was suspended upside down over a well by a frayed rope, her father was beaten with ox-whips and the cow (through the fault of an over-zealous corporal) kept under strict surveillance. They proved however, to know nothing of the plan which, after three days of deep deliberation, the General Staff had evolved.

This was the plan:



The circle represented the fortifications of Lanka, ignoring small deviations in the course of the walls to accommodate the lie of the land. The letters A represented the disposition of the armed forces of the allies. That is to say, the letters A represented the places where the forces were at the time of the deliberations of the General Staff. The letter B represented the place where they ought to be at the end of the campaign. The tactical manœuvre which the generals had evolved consisted in a movement, duly co-ordinated and begun at the most favourable moment, from the points A to the point B. In view of the intervention of the wall, the generals had decided that this manœuvre, the only one militarily sound in the circumstances, called for more bows, more arrows, more scaling ladders, more moveable turrets, more chariots, more sappers, more miners, and more money than they had at present got. This plan was laid before Rama, who, asking if they would also require more generals, was told that they had, fortunately, enough.

Shortly after the formulation of this master plan, a young soldier from the Nilgiri Hills was crawling among some bushes which surrounded the foot of the walls of Lanka in search of fennel, the taste of which in his curry he was inordinately fond. Having made his way for a considerable distance round the walls, he came across two outlying towers joined to each other and to the main fortifications by curtain walls. Observing no sentinels, he approached the curtain walls, which seemed to be broken in places and therefore a good place in which to find fennel. He did not find his herb, but he found something which interested him even more—the broken part of the wall constituted a breach ten feet wide that had been hastily repaired by piling the fallen stones loosely one upon the other. These had again fallen down in part, and it was possible for a man to walk through the gap. The young soldier being a hardy mountaineer who did not know what it was to be afraid, promptly walked through the gap. He found himself in long grass which, growing higher than his head, gave him excellent cover. Moving cautiously through this he came up to what should have been the main wall behind the outlying towers, but which was in fact, merely a foundation two feet high, the wall itself having been destroyed, whether by an earthquake or by some previous enemy he could not tell, and which had never been rebuilt. He returned immediately to the camp with his news. After a brief court-martial he was condemned to death as a spy sent by the enemy to lure the allies into an ambush.

The unfortunate man appealed to Rama, who, in great perplexity, spoke to Valmiki, who had accompanied him to the field of war. Valmiki said:

"Either you must execute the soldier or you must execute your General Staff. I recommend you kill the soldier. It is an accepted principle of warfare that when generals make mistakes it is the soldiers and not they, who get killed for it."

Since there was no disputing this, Rama reluctantly confirmed the sentence, but mercifully commanded that instead

of being trampled to death by an elephant, the man should be strangled with a bow string.

The generals, nevertheless, sent reconnoitring parties to spy out the breach, which they did with so much noise and alarm that the defenders of Lanka were made aware of their danger and immediately repaired the gap. The Lankastrian sergeant in charge of that section of the walls had previously reported their defenceless state, but his advice had gone unheeded in the press of business. This business consisted in drawing up their own tactical plan for the raising of the siege. It was based on the supposition that Lanka was now completely surrounded by an impenetratable ring of armed men. In view of this there was no possibility of help coming from outside and the only hope for Lanka was clearly to prepare for a long siege and to wear down the enemies' will to fight by the stubbornness of its resistance.

A married soldier impressed from a village some ten miles away having been seized by an ungovernable desire to sleep with his wife, let himself down one night over the walls of Lanka, and with no more difficulty than having to lie still while an infrequent sentry passed, made his way safely through a gap in Rama's lines into his wife's arms. He, however, was too wise to return. He stayed in his village until the battle was over and for some fifty years afterwards. In his old age he was fond of telling his grandchildren how he escaped the great slaughter of the siege of Lanka. They listened to him politely but did not hold him in any great esteem.

•

Preparations now began for the assault but this was delayed by an unforeseen event. The generals had set much store by a mace which had been designed by an ironsmith who was married to a daughter of the senior general. This was unlike the maces generally in use. It ingeniously employed the momentum which the wielder gave it in striking at his enemy to lay low one at least of the soldiers on either side of the adversary. In addition to the normal spikes this mace

had a heavy iron ball attached to a chain which in turn was stapled to the mace's top. Special exercises were decreed for the troops to learn the use of this novel weapon. But on the first of these it was discovered that the mace was too heavy to be lifted higher than a man's navel.

The general who was the father-in-law of the inventor was greatly chagrined, and although he could not be said to have been wrong, since he was the senior general, he felt that he owed it to his position to insist upon fresh and sturdier troops. A detachment of near-giants from the Carnatic were brought with all possible speed to join the forces. These found no difficulty in raising the mace but being men of an impetuous nature not too well endowed with intelligence, each exercise very nearly halved their numbers since the balls struck their companions as frequently as they struck the stakes that represented the future enemy. The general, however, was content. He pointed out that the introduction of the new weapon had proved a stiffener of the army's morale, since it gave such troops who neither used it nor were near it, confidence, that in the matter of inventive military science, they were the Lankastrian's superior.

The bustle of preparations was diversified by a comic incident—although tragic in its outcome for one participant—that caused much amusement in the ranks. An unknown apothecary waylaid every officer he could in an attempt to interest them in a black powder which, he said, when ignited, would explode with such force that if placed in a suitable tube, it would raise a heavy projectile high enough in the air to go over the walls of Lanka and to descend, destructively, inside the city. This charlatan—or crack-pot, for opinions about him among the generals were divided as to whether he was a swindler or a lunatic – became such a nuisance that the senior general finally ordered him out of the military lines. He was twice found peddling his black substance after this. On the second occasion he was bound and seated on a keg of his own

powder, and a torch was applied to it. There was a deafening report and although it was impossible to see if he had actually risen higher than the walls of Lanka it was generally agreed, with much hilarity, that a part of him might well have done.

Valmiki, who witnessed this punishment, remarked to the senior general that the powder was certainly as effective as its inventor had claimed. At which the senior general clapped the poet on the back and said: "So it was; so it was. And it would be a damned effective weapon, if only we could get all the enemies' soldiers to *sit on the kegs.*" This remark raised a general laugh against Valmiki, in which the poet, in so far as his grin grew even more marked, was seen to join.

II

The Challenge

THE preparations for the fighting went on for three months, for there is no person more pacific than a military expert once fighting is inevitable. There are a thousand details to settle, innumerable exercises to perform; if an army marches on its belly, a General Staff wins campaigns on its backside. When the later historians of this famous war speak of the allied army sitting down around the walls of Lanka, so far as the higher command was concerned, they do not speak metaphorically.

We must now return to Luxmun, who, as we know, was a more impetuous type of soldier.

It was Luxmun who had brought about the great alliance for the rescue of Sita. It had therefore been agreed by all the rajas and even by their staff officers that Luxmun should be given a post of high authority in the expedition. They had suggested this to Rama who readily agreed. Rama would not have accepted, in any case, a different arrangement. He loved his brother, although he rarely spoke of his affection, and never (more importantly) thought about it. It follows that his love was a real one.

With very little debate Luxmun was given the post of Commandant of the Royal Guard, a name given to a body of some five hundred picked men whose duty was to guard the person and the standard of Rama in battle. Among the prerogatives of his rank were the right to fight from a battle-car, or chariot, the right to have his own bodyguard of ten men, and freedom to forage and loot as the fancy took him. These privileges pleased him: one other did not, and that was the right to a place in the planning conferences of the General Staff. He begged to be excused this duty, but

his brother insisted, saying that Luxmun as a prince of royal blood, could not, with honour, refuse. Luxmun, as always, obeyed his brother, and went.

Rama was sometimes present, but not always. When he went he felt that he owed it to his position to speak. When he spoke the military men felt that they owed it to his dignity to listen. They also felt that they owed it to their own dignity never to follow any of his suggestions. Rama, noticing this, more and more frequently appointed Luxmun to represent him, with the duty of telling him what had taken place.

Luxmun was able to follow their tactical plans for the siege of Lanka, but he confessed that the general conversation of the warriors puzzled and dismayed him. Although Luxmun had done a great deal of fighting—rather more, he discovered, than some of the generals—they had only to begin discussing a past campaign and Luxmun was immediately lost.

"It's all flanks and wings, as though they were talking about a hawk catching a hare, instead of war," Luxmun complained to his brother. "When I mention something out of my own campaigns like hitting that big black mercenary on the head in the Battle of the Waterfalls—you remember? —and he wouldn't fall down although I hit him right square on his helmet with the spike of my mace—I've told you, haven't I?—so I hit him again—clang—and again—clang—clang—and he just grounded his spear and leaned on it—remember?—and there he was leaning stone cold dead, leaning, you see—well, they look at me and make me feel crude. I don't understand all this business about the art of war."

"Neither do I," said Rama. "Let us go and ask Valmiki to explain it to us. Valmiki is certain to understand it because he knows everything.

Valmiki disclaimed the honour of knowing everything but admitted that he had made a study of the Art of War.

They visited him in his pavilion which was of saffron-coloured silk (Rama had chosen this unmartial colour for him to distinguish it from the tents of the warriors) and he invited them to seat themselves on the Sindhi rugs which lay three deep on the floor. Rama and Luxmun repeated what they had been saying to each other concerning the difficulties of strategy and tactics, and asked Valmiki to help them.

"I have never fought in a battle," said Valmiki, "and indeed I have never been near an army until now, but I have always been deeply interested in the theory of the matter. I have talked to the best authorities and I have recently had the advantage of listening at great length to the reminiscences of your General Staff. I shall now explain to you military tactics.

"There are three theoretical ways of winning a battle. You can attack your enemy in the middle of his line and put him to flight. This is called crushing his centre and is considered rather jejune. Or, you can go round by his left side and roll up his forces while they are looking the other way. This is called turning his left flank and is considered highly ingenious. Or, again, as I scarcely need explain you can do the same thing at the other end, which is called turning his right flank, and is considered equally clever."

"It sounds very simple," said Rama.

"So far," replied Valmiki. "But you must remember that the opposing general will also be using tactics. That is to say, instead of obliging you by retreating, while you are crushing his left flank he may be crushing your left flank. In that case you must withdraw forces from your left and send them to your right. Observing this, the opposing general withdraws forces from his left and sends them to attack *your* left. Meantime a great deal of hullabaloo will have been going on in your centre. Things thus grow more complicated but not impossibly so."

"They would for me," said Luxmun, who had been tugging at his moustaches and frowning. "The trouble with

me is that ever since I was a boy I have always got muddled about which was my right hand and which was my left—if I had to remember quickly, I mean."

"After a prolonged study of the descriptions of many famous battles," said Valmiki, "I have come to the conclusion that several generals have suffered from the same embarrassment."

"Wouldn't it be simpler," said Rama, "if each opposing general wrote his plan down and put it in a box. Somebody who is constitutionally impartial, like yourself, could open them and work things out and declare the winner."

"But that would be an impossible plan," said Valmiki, shrugging his bowed shoulders and grinning, "because in that case the cleverest general would always win."

"What would be wrong with that?" said Rama.

"From the point of view of the stupider general, everything," said Valmiki.

"But the stupider general is bound to lose, anyway," Rama protested.

"Oh by no means," said Valmiki, his eyes glowing with amusement.

"I can vouch for that," said Luxmun. "Some of the orders I've been given have to be heard to be believed. Still, I've usually come out on the right side."

"Among the best authorities on military tactics that I have consulted," Valmiki said, "have been the foot soldiers. What they have to say is very interesting especially when you take it together with the descriptions of great battles that have been written in our chronicles. You will find that battles are not lost and won at all by turning flanks or crushing the centre or moving reserves. What happens is more simple. Among the decisive tactical events that I can recall at the moment I may mention the occasion when one general forgot that horses do not easily leap a thirty-foot ditch but customarily fall into the bottom of it. That blunder cost him half his cavalry and the whole campaign. Or there was the even simpler error when all the generals on one side

forgot that their troops had not been paid, so as soon as the fighting began they went over to the other side. Then again there was the general who chose a site for his battle which was perfectly adapted to a most brilliant flanking movement which he had planned, except that he had not noticed that it was a bog. Nor must we forget the general who always made a point of sleeping soundly the night before a battle to set an example to his men. Unfortunately he set an example to the enemy, who stayed wide awake and won the battle between two and half-past two in the night before it was supposed to be fought. Then there were battles which were lost because of the enemies' ruses. These ruses are the most interesting aspect of all for the thoughtful observer. They consist in such things as troops lying in the long grass and jumping up at the last moment, or pretending to run away so that the opposing forces run after them and straight into an ambush—tricks which might perhaps deceive a schoolchild once but which could not possibly deceive him a second time. Yet you will find if you study our histories that they have dumbfounded our military experts time and time again. Thus, my friends, you will see that tactics are by no means the deciding factor in warfare which, after all, is a chancy thing and the chanciest thing about it is the intelligence of your generals."

Rama thanked Valmiki for his instruction and told Luxmun to do the same. Luxmun obeyed, but with an abstracted air.

"What do you think?" said Luxmun when they had left the tent and were walking back to their own between the rows of gleaming pavilions, from each of which streamed pennants with the fighting symbol of its resident—lotuses done in silver thread, tigers in yellow silk from Peking, prodigious maces worked in gold, or delicately carved bows in padded embroidery, strung and with the arrow ready for discharge.

"About the art of war?" asked Rama. "Valmiki does not appear to think highly of generals but then he does not

think highly of anybody who sets themselves up to know better than the rest of us. Besides, even if generals are as stupid as he says they are—and I don't doubt that he is right—he is not so lightminded as he tries to appear—still, I do not see what I can do about it."

"I think I do," said Luxmun, but Rama did not hear him, for at that moment there arose a great bellowing and trumpeting from some elephants that had just arrived in camp. They had been brought from the jungles of the south with enormous difficulty, and Rama hurried away to see them, eager to find out what use could be made of elephants in a siege. After diligent enquiries he discovered that nobody knew; but that there was a widespread impression among the more experienced officers that a few elephants were always a great comfort.

That night Luxmun gave a feast for some of his friends among the Royal Guards. It was held in his pavilion and was a very boisterous affair. Had anybody lifted the closed flap of the inner tent to observe the jollity, he would have seen that instead of ten soldiers sprawling around a drunken Luxmun in the height of an orgy—which was what the noise suggested—there were ten preoccupied men methodically singing songs, clanking brass dishes and bursting into laughter at signals from an efficient captain. And he would not have found Luxmun.

Rama's brother was, for the first time that he could remember, taking action without Rama's consent. Fearful that his brother would discover his intention (for in spite of his moustaches, Luxmun had no art in concealing his thoughts) he had asked some of his friends to make the pretence of a soldiers' party, from which, he was well aware, Rama would stay away, such routs not being to his liking.

Luxmun meanwhile stole through the lines wrapped in his cloak. Giving the password to one of his own men who was on guard at a point opposite the city, he swore him to secrecy, and then moved quickly out into the open space between his own lines and the walls of Lanka.

These walls towered blackly above him. He drew near and struggled to suppress the sound of his heavy breathing. He listened for some while to the tramp of the sentries, and judged the passage of the nearest as he walked between two turrets. When the sentry was at the furthest end of his beat, Luxmun unwound a rope from his waist to which was attached a grappling hook. He swung it and it fell between the crenellations which were shaped like large leaves. The noise attracted the sentry, who came running to the spot, calling his fellow-guards. It was not part of his design, but Luxmun, seeing the man's head against the sky loosed off an arrow at him and shouted an insult. Then he retired out of range of their bows and strained his eyes in the darkness to watch what they did. The darkness was soon relieved by the light of torches. The sentry, and, it seemed, some companions now began raining darts at the point where Luxmun had stood. They did not see the grappling iron for so long that Luxmun shouted and told them it was there. Then they saw it. They pulled at the rope and Luxmun heard them say there was nothing at the end of it. But in this they were mistaken. When they had pulled up the end of the rope they found a long flat palm leaf into which a message had been cut with a stylus and rubbed with charcoal dust to make it easier to read. Luxmun gave them a last shout and told them to take it to their master Ravan.

When they had done so and Ravan, awakened, had sleepily put together the meaning of the symbols he found this message:

> '*Ravan, King of Lanka. I, Luxmun, the brother-in-law of the Princess Sita, have come here to protect her honour. But now I am going back home because since I have seen your cowardice in not giving fight, I do not think my sister's honour is in any danger since you are not man enough to have attempted it.*
>
> LUXMUN,
> *Commander of the Royal Guard of Rama.*'

III

Single Combat

THE next morning, two hours after the sun had risen, all the war-trumpets of Lanka rang out from the battlements. These war-trumpets of Lanka were not carried by men, like those of Rama and all other Indians. They were horns so long that they rested, fifteen feet away from the mouth of the trumpeter, on bronze stands wrought in the shape of slavering demons. They were grim to see; unseen, they were more terrible still.

Each trumpeter had a different note, but each had only one. When they spoke, twenty of them, from the walls of Lanka, it seemed as though a score of angry lions were roaring in a brazen cavern.

In Rama's army the morning bustle was stilled; men ceased their exercises and gathered in groups with their comrades. Rama and Valmiki came to the doors of their pavilions and gazed towards the city.

At the third sounding the commanders began to marshal their forces. The men moved quietly about their business but the animals—horses, elephants, camels, and mules—disturbed in their very bowels by the trumpets, grew restless and complained, their braying, bellowing, and long, high-pitched whinnies, making the nerves of their owners still more tense.

Rama spoke to the generals who were near him and all predicted an attack. Rama called his armourer and went into his tent to prepare for battle. Soon his war-chariot came to the pavilion door, shining with its bronze plates, the great quivers at the sides filled with arrows, its horses jingling their traces in a restless dance from hoof to hoof.

Then, armed cap-à-pie, riding in his chariot, Luxmun, his eyes gleaming, took out a body of the Royal Guard all fully accoutred, as they had been since sunrise. He took up a

position opposite the gates of the town but a quarter of a mile away and there in a short while Rama and his principal allied rajas and their officers joined him, each in his war-chariot and ready for combat.

The trumpets of Lanka sounded again. The great doors of Lanka began to open. As the echoes of the trumpets died away the voices of Rama's officers could be heard putting their troops in readiness for the expected sally.

But only a single horseman rode through the half-opened gates.

His horse was a handsome bay. He was dressed not in the heavy panoply of war but in the light, fanciful armour of the Court. His helmet was no more than a golden cap; light mail sparkling with jewels covered his chest, and his soft leather sandals rested lightly on his stirrups which lacked the shovel of bronze that in war protected his feet. He carried a lance from the point of which dangled a metal object that could not be clearly made out until he rode closer. Then it was seen to be a small perfume bottle. He rode with insolent unconcern right up to the ranks of chariots. He bore no sign or pennant to show that his mission was that of a herald, but his manner was sufficient to protect him.

He halted his horse directly in front of Rama, coolly surveyed him from head to foot, and then did the same with the principal allies. He moved slightly in his saddle, and looked at Luxmun, saying:

"I seek the brother of Rama."

Luxmun put up his hand to his moustaches, and shook his shoulders till his armour rang.

"I am Luxmun."

The herald looked him over, but gave no sign that he had heard him. Instead he moved his horse slowly away to the right, walking past the guard, past the company of archers that stood next it, until he came to a group of men armed with slings. Mingled with these were youths with bags slung round their shoulders who carried the smooth round stones that were the slingers' ammunition.

The herald reined in his horse. Choosing out a beardless boy who stood gaping in the front rank he bowed his head ironically and addressed him:

"My Lord Luxmun: greetings."

The boy's jaw dropped further and he stared at the elegant herald wide-eyed.

"My master the serene and powerful Lord of Lanka, and descendant of the Gods, Ravan, King, bids me tell you that he has received your message. He sends you his royal thanks."

Here the herald bowed his head again to the boy, who blinked his eyes at the dazzle from the herald's casque. The herald spoke again, loudly so that his words carried far along the line of soldiers.

"In return he sends you this present."

The herald slowly lowered his lance until the point was level with the boy's head. The boy unthinkingly put out his hand to take the dangling perfume bottle, but the herald jerked the lance forward so that the boy fell back against the slingers behind him.

"It has been recommended by His Majesty's Chief Barber." declaimed the herald, "as the best recipe that is known for making the beard grow on the beardless chins of younger brothers. His Majesty's Chief Barber adds that the liquid must be well rubbed in. If, Luxmun, you do not know how this is done, my master, the serene and powerful lord of Lanka, and descendant of the Gods, Ravan, King and mighty warrior, will come here before these gates at noon tomorrow and do it for you."

He jerked the lance and the bottle fell to the ground at the boy's feet and the slingers scrambled to pick it up. The herald wheeled his horse and rode slowly back to where the real Luxmun stood in his chariot, flushing with anger. The herald again looked him over with deliberation, but this time there was a smile on his lips and a quizzical tilt about his eyebrows that showed plainly that he knew and had known who Luxmun was.

Luxmun did not move. The herald turned his horse towards the gates. His horse moved a pace forwards and then, as though the herald knew that the magnificence of his bearing would no longer protect him once he had turned his back, he kicked his horse's flanks and made for the gates at full gallop.

With this retreat of the herald, Luxmun, whose tongue had been bound with shame and rage, suddenly found words, a torrent of them, which he shouted at the fleeing horseman, accepting the challenge and offering to fight any high-born soldier in all Lanka, one by one, after he had killed Ravan. The whole watching army waved its approval and the horseman made the last few yards of his perilous withdrawal bent low over the neck of his horse, as darts, stones and arrows fell around him. The missiles rattled on the great gates as they opened slightly to receive the horseman to safety and then closed, as, once more, the long trumpets sounded from the walls.

That evening Rama went to Valmiki's pavilion and sat wearily on the rugs. Valmiki served him with pomegranate juice.

"Thank you," said Rama. "I know only one thing as calming as pomegranate juice and that is to listen to your reprehensible opinions. The generals have objected to Luxmun fighting Ravan tomorrow."

"It is one of the things, like the ditch, which are not foreseen in the art of war," said Valmiki. "They will naturally object."

"They wanted me to stop him," said Rama.

"And what did you answer?"

"I said that it seemed to me that what they wanted me to do was not to stop him fighting tomorrow but to stop him sending the message that he delivered to Lanka last night. Once he had done that, nothing could prevent the rest."

"It is exactly the answer I would have made myself," said Valmiki.

"Yes, I fear so," said Rama, smiling. "I find that I have been infected with your way of thinking."

"You regret it?"

"No," said Rama, and sighed. "But it does away with a lot of romance and speculation and fine speeches and wonderful despairing thoughts."

"I find it a little earthy myself," said Valmiki. "After all, it was very pleasant to be young."

"It was," said Rama. "It was."

A quarter of an hour short of noon the next day Rama unarmed received three priests in saffron robes from Lanka and pledged his honour as a prince that the rules of the combat should be observed: namely, that the contest being between princes of royal blood, it should take place in chariots, each prince to have his charioteer; that the contest should take place between the gates of Lanka to the one side, the standard of Rama to the other, a stone pillar to the left and a tree to the right, the space thus defined being a square some three hundred yards across: that each prince should be accompanied by three horsemen, of noble birth, who should take no part in the contest; that the contest should begin by the sounding of a conch shell by the horsemen of the challenging prince; should continue until one prince surrendered, or was killed, or fled the field; and should one die, then the other should forthwith take a white goat and kill it upon the altar of the God of War, to bear the guilt of the slaying.

The Brahmins retired into Lanka. Rama's army lined three sides of the square and there were men on every vantage point in the city, some even on the high pyramids of the temples within. The sky was a hard blue and the heat of the day had already set the air at the bottom of the ramparts quivering.

Rama saw that on some of the rooftops in Lanka women had gathered. He searched among the tiny, bright-clothed figures, but whether Sita was among them he could not say, for they were too far off. He thought of his wife deliberately,

and endeavoured to do so with tenderness: but he could not, for the picture of his brother lying in the dust beside his chariot supplanted all others, and Rama felt cold under the midday sun.

He went to speak to his brother who stood patting his horses' necks and speaking to them. He took his brother's hand, but feeling his own tremble, he released him and left him without speaking. No sooner had he regained his position among his Royal Guards, than the great doors of Lanka opened.

The three noble horsemen came out at a gallop, riding in great arcs before the chariot of Ravan. The chariot rumbled out of the shadow of the gateway and tongues of flame seemed to leap from it as its two black horses pulled it into the blaze of the sun. The pole between the horses was of burnished bronze, the chariot's high front behind the crouching charioteer was of brass, polished and studded with square-cut nails, and the wheels, spinning in the dust, made discs of light with their metal sheaths.

The charioteer crouching on a footsquare platform at the butt of the pole between the horses shouted, half stood, and leaned back on the reins. The black horses reared in the air and the chariot came to rest. Then all could see, standing upright with only one bare hand to steady him, the awesome figure of the King of Lanka.

Tall as he was, he was made taller by his helm of black iron with silver bosses across the front, and made terrible by the iron strip that stretched from his forehead to his upper lip. His body armour was black like his helmet, but a sash of gold with a jewelled clasp hung loosely around his waist. His loin-cloth, tight folded between his legs, left his great thighs bare. He rested upon his mace, a stout bar of iron that ended in a spiked ball and which was bound to his wrist by a leather thong.

The noblemen reined in their horses behind him. The charioteer crouched again over his pole and Ravan waited, upright and unmoving.

The chariot of Luxmun now came into the lists, at a slower pace, for he had not the advantage of driving through a gateway, but came from before his pavilion, his noblemen trotting beside him. But his white horses, the golden ornaments of the cedarwood chariot, and the silvery gleam of his body armour and burnished iron cap, gave him grace and ease. He took up his station.

Ravan's three noblemen now rode to the centre of the field, and Luxmun's supporters did likewise. They faced each other in two ranks, Ravan's men heavy, insolent and swaggering: Luxmun's slighter in build and less certain of what they had to do.

There was an exchange of courtesies. One of Ravan's nobles raised a matter of the rules, but the watchers could not hear all that he said. The point was settled as the horses stamped and jingled their harnesses. The six horsemen galloped off the field to its edge and the last of Ravan's men turned in his saddle and put a conch shell to his lips. Its long, melancholy note echoed for a moment from the walls of Lanka, and then was lost in the shouts of the two charioteers.

To Rama, watching, it seemed as though the two chariots drove straight at each other. But as they were about to meet in the middle of the field, each charioteer turned his horses very slightly and the chariots passed each other, wheel all but touching wheel. Ravan and Luxmun swung their maces and leaning over the sides of their war-cars, struck at each other. The impetus of his chariot and his mace betrayed Luxmun's judgement. His blow missed its mark and the end of his mace struck the wood of Ravan's chariot, splintering it and buckling its metal plates. At the same moment Luxmun felt a blow on his left shoulder that sent him reeling against his charioteer and deprived him, for a moment of his sight. The charioteer held him up with his shoulder as he brought his horses round in a tight circle. The chariots passed again and Luxmun, unable to gather his strength quickly enough, bent all his wits on parrying Ravan's next blow.

He swung himself into the position for striking a blow himself. Ravan, seeing this, was deceived into thinking that his first stroke had done Luxmun no harm. Had he known that Luxmun meant to parry and not strike he would have changed his stance at the last moment. He did not. He struck downwards and his mace fell upon that of Luxmun. The shock sent a great wave of pain through his spine and his anger flared.

The chariots came together for the third time. Ravan swung his mace but his hot blood made his stroke clumsy. Luxmun, his nerves steady, made as though to aim at Ravan's helmet, but as the chariots passed each other, changed his stroke by a great wrench of his wrist and brought it down upon Ravan's breast and shoulder. The spikes drove home through the links of the armour and the black lacquer turned red with Ravan's blood.

Seeing this a great shout came from Rama's army and Rama rejoiced aloud.

But now the chariots did not draw so far apart. By the rules of single combat they must now keep as close to each other as they could, each man fighting continuously till the end of the battle.

The three horsemen of Lanka rode forward: the three of Rama did the same. The six stationed themselves at six points that formed a rough ellipse. Within this, the chariots must manœuvre. The two chariots turned in a narrow radius and instantly it could be seen that Luxmun's car had the advantage. It was lighter than Ravan's and more easily handled. The chariots came close, withdrew and closed again, Ravan and Luxmun balancing on the balls of their feet and striking with their maces at each approach.

To wild shouting from Rama's soldiers, Luxmun's strokes again and again found their mark, and although the blows that could be delivered in this twisting and turning phase of the duel had not the force of the first tremendous strokes, they wounded Ravan; when his chariot wheeled away it could be seen that he was bowed with pain. He seized

his charioteer's arm to steady himself and he spoke to him.

The two chariots approached again. The dust rose in a great cloud around them: but it was not enough to hide what happened next. Luxmun's chariot came up, wheeled, and lay broadside to Ravan for a moment. Ravan's chariot feinted as though to turn as the rules demanded, but the charioteer rising from his narrow platform, struck his horses with his whip and drove them straight into the flanks of the horses of his enemy. The bronze-shod pole shot at the terrified white horses like a spear. The horses whinnied with fear, jerked their reins from their driver's hand and pounded the air with their forelegs. Luxmun's chariot reeled drunkenly. At that moment Ravan's horses were brought sharply up on their hindlegs and Ravan, leaning out of his war-car, struck Luxmun to the floor of his chariot with a single blow. As Luxmun's horses bolted away, he was flung out upon the ground, where he lay without moving.

The three noblemen from Rama's army galloped towards the witnesses from Lanka shouting their protests. The men from Lanka hesitated: then a shower of missiles from Rama's roaring, cursing, and enraged army fell about them and, calling to their master, they put spurs to their horses and rode for the gate. Ravan's charioteer, whipping his horses, followed them. But his trick in driving at Luxmun's horses had strained his harness. It broke, and Ravan's chariot slewed in the dust.

Instantly the soldiers of the Royal Guard charged to capture Ravan, and the rest of the army in wild confusion began to follow them.

A mounted group of men from Lanka, rode out from the gates and laying about them with great ferocity, protected their King, and, slowly retreating with him, took him at last safely within the gates, leaving many of their number dead on the plain.

Luxmun, coming to his senses, found his brother leaning

over him. He saw his broken chariot and looked for his charioteer. He smiled when he saw that he was safe. He listened to the din of the battle that now raged at a hundred different points and he smiled more broadly.

"We're attacking?" he asked.

"Yes," said Rama. "There is no holding the men back."

"At last," said Luxmun; and then, "How very angry the generals will be with me."

For the next three days the siege of Lanka was waged by all branches of the army with the greatest confusion and high spirits. Attacks were launched and repulsed again and again, their leaders having no more plan than to outdo the next body of men in the line. Whenever, for reasons of exhaustion, there was a comparative orderliness, the generals seized it as a favourable moment to regain control. Things would go for an hour or so according to their carefully laid plans, but this did not, in the end, sensibly diminish the confusion.

Even the elephants played their part. They were led against the gates of Lanka in an abortive assault. Most of them, with the sagacity for which they are famous, surveyed the forces ranged along the walls on either side and returned to their stables at a fast trot. Three were killed by huge iron darts dropped from above. Their carcasses lay against the gates affording extra defences for the Lankastrians

But the confusion within the town seemed no less than that without. The defence slackened and in the morning of the fourth day since the combat it was decided in Rama's camp to make a full assault. The siege engines cast flaming balls of flax, a ram battered the gate, towers were wheeled towards the walls and the messengers running between the generals ran so often that they fainted with exhaustion.

At last the gate gave. Rama, placing himself at the head of his Guard, led the assault and entered upon his first taste of warfare, climbing over the carcasses of the elephants.

The fury of the assault, all the more terrifying for being virtually unplanned, dismayed the Lankastrians on the

walls, who also had good reason to fear that all was not well behind them. They yielded. The gates fell. Rama, on foot, cut his way into the streets of the city. He had killed four running men before he discovered that it gave him a tremendous and bloodthirsty joy.

He performed prodigies as they fought their way to the Palace. He killed the single loyal guard outside the private chambers of the King with one thrust. He broke through the door with the aid of the closest of his own Royal Guard and found Ravan dead upon the floor. Ravan's eyes and tongue protruded. His fingers had been lopped off to get his rings. A heavy chest that had once contained treasure had been flung across his legs, breaking them. His chosen companions, the soldiers who had sacked the hermitage, had seen no reason to change their ways merely because their master had been defeated.

A eunuch crawling on the floor, offered to show Rama the room of Sita.

Rama went there at a run, and burst into the room. Sita stood by a couch, a short sword in her hand and a soldier jerking in his death agony at her feet.

She looked at Rama, as he stood panting, his forearms covered in blood, and blood on his face. She looked at the sword in her hand.

"Let us go somewhere to clean ourselves of this filth," was her greeting to her husband, "and become human beings again."

But if a bath in Ravan's own bath could make Rama a human being again, nothing could make him an ordinary one. To kill one or more persons is always the shortest path to a rapid change in one's life; done at the wrong time, it results in the gallows; done at the right time, it leads to fame. Rama's killing had been, in fact, no more than a street-fight. But his timing had been magnificent as it so often is with those who seem born to lead. He became overnight, a

hero. It was said on all sides that he alone had been responsible for the capture of the city.

This credit really belonged to the soldier whom Sita had killed. He was a jealous cousin of Ravan's who had spread the rumour that the town had been betrayed and then, when he had helped to murder the King, had gone to capture Sita. He, however, now lay dead in a gutter into which his body had been kicked, while Rama sat on Ravan's ebony and silver throne. Rama's name rang throughout the land.

He had won a great victory; he was the master of a devoted army. There was nothing that was not in his power to do, if he wished it. Although it would seem wise to suspect such a man of the worst intentions, in practice the world tumbled over itself to think the best. Embassies arrived in Lanka daily, among them one from Ayoda announcing the death of his father the King. Rama kept the embassy waiting three days and then refused to discuss his return—for which they begged—on the ground that he was in mourning. He shut himself up, and it was given out that he was fasting and praying for the salvation of his father's soul.

He was, however, thinking of Sita. When he had appeared in the streets of Lanka his soldiers shouted "Long live Rama!" When Sita had appeared, they cried, "There goes the whore!"

In the cool of the evening Luxmun would sit on the paved roof of the Palace, taking the air, and fretting at the time it took for his wounds to heal. There, soon after the coming of the embassy from Ayoda, Sita joined him. They sat silently for a while, listening to the noises of the city below.

"He won't see me," said Sita, at last. "He won't even speak to me."

Luxmun blew his moustaches indignantly.

"If he hanged the next ruffian who shouted at you in the street, there'd soon be an end to it."

"An end to what?" said Sita.

"The—shouting," said Luxmun, and flushed deeply.

"Yes. That's what I thought you meant," said Sita. "You think it's true, don't you?"

"I don't think anything's true," said Luxmun, violently. "Lies: all lies and I'd like to see the man stand up to me and say it isn't when my shoulder's better."

"So you do think it's true," said Sita, and looked away.

"What? I don't know what you're talking about."

"That I'm an unfaithful wife and I've slept with Ravan."

"You didn't do anything of the sort," said Luxmun. He struck his knee and winced with pain.

Sita said:

"I did."

Luxmun said nothing for a long minute. Two drunken soldiers quarrelled near the Palace and their obscenities came drifting up on the evening breeze.

"He made you, Sita. He forced you."

Sita shook her head.

"Ravan was cruel and he was a monster when he went on his raids. But with women he was gentle. No; it was in the bargain, but he did not press me to keep it."

"Ah!" said Luxmun, "so there *was* a bargain. I thought so."

"Yes. I made up my mind when your bow-string snapped on the night they destroyed the hermitage. You looked round and I saw your face and I said to myself Luxmun's getting ready to die."

"A soldier's always doing that, Sita."

"Not a good soldier. He only does it once, when he knows that there's no hope left. That's what you knew, then."

Luxmun nodded.

"There was nothing to get our backs against," he said. "They had only to come down the hillside and they could have picked us off just as they pleased. So that's why you said you'd go and get the bow-string?"

"Yes. It wasn't very difficult to make up my mind, but

I had no time to explain—especially to Rama. He never was an easy man to explain things to."

"He's changed," said Luxmun. "He's changed very much."

"Perhaps. Still, what *was* very difficult was to cross that space in front of the house with the soldiers shooting everywhere. I kept telling myself that if nothing hit me it was a sign that what I was doing was right."

"Just what I'd have done myself," said Luxmun.

"Nothing hit me. When Ravan saw me, he stopped the shooting. When he heard that I'd go with him if he'd stop the killing and torturing, he stopped that too."

"You were very brave."

"Yes, I was, Luxmun. I'd have been a heroine. I meant to be. I meant to kill myself rather than keep my promise. I think I would have killed myself if he'd have come at me as I expected, all drunk and brutal. But I hadn't allowed for one thing."

"He played a trick on you, eh?"

"Yes, Luxmun. The oldest trick of them all. He just said that he loved me above everything in the world and that he would never force me to do anything I did not want. I was pleased at first. Then I was sorry for him. Then he kissed me. Then I wasn't a heroine any more."

"I see," said Luxmun. "Well, you could be sure a fool like me would let you down."

"You?"

"Of course. I had three chances to kill the swine—*three.* Once in the glade, once when he came to the hermitage right under my nose, and once more when I fought outside these walls. I failed each time. It's all my fault, and I know it."

Sita, hearing this, pulled her sari across her face: for the first time since the fall of the city, she wept, and very bitterly.

Luxmun got up, watched Sita for a moment, and then left her.

When she next saw him, he came bursting into her room his face aglow, his extravagant moustache in utter disarray.

"Quickly!" he said. "Dry your eyes! We're going to Rama."

"Have you seen him?"

"Seen him, talked to him, and given him a piece of my mind. What d'you think of that?"

"You?" said Sita, incredulously. "*You* gave Rama a piece of your mind?"

"I have," said Luxmun, and then, with awe at his own daring, he repeated, "I have. I felt I had to do something since I had failed you so badly. I found Rama with Valmiki. The moment I mentioned your name Rama turned his back on me. But I shouted a bit, and I made him listen to the whole story. Then I told him that if he didn't forgive you, I would pack up and leave him for good and go for a soldier in Persia or somewhere. 'And what's more,' I said, 'I shall be sorry I ever had you for a brother.' Stupid thing to say, wasn't it? But Rama turned quite pale. He took my hand and called himself a lot of names that I shan't repeat. And he said he was sorry. And he forgave you. So he should. He loves you, you know."

"Not only me," said Sita.

When she met Rama again they saluted each other gravely and got down to business. This was quickly despatched. Rama told her that he wished to go back to Ayoda and accept the throne which was offered him. He had been turning over in his mind the best way to allay the scandal. He had consulted Valmiki. On the poet's suggestion he had decided to award her, here and now, the titles of *First Queen* and *Most Faithful Wife*.

When he had said this, there was a moment's silence between them. Then Sita smiled, and Rama smiled in return. After that, they embraced. Later that night, lying side by side in what had once been Ravan's bed of state, they agreed that during the time that they had been apart, they had both grown considerably older; though not (they assured each other, embracing again) in their looks.

IV

The Tale of the Stone Woman

THE next day, somewhat late in the forenoon, Rama called the ambassadors from Ayoda into his presence and told them he had decided to return to his native city and to take up his inheritance.

The ambassadors prostrated themselves with shouts of joy and for the first time in his life Rama heard himself addressed as "Your Majesty". At first it sounded well in his ears. In the course of the next hour he heard himself thus addressed some two hundred and fifty times as each of the ambassadors, unfortunately no longer prostrate, made him a eulogistic speech.

Rama listened with what he hoped was a kingly expression, but the pleasures of the night before had been fatiguing. Rama yawned, Rama nodded, and Rama fell soundly asleep.

An attendant touched his elbow and he awoke. The last of the ambassadors, observing that he once more had his monarch's attention, began his speech all over again.

"My poor father," said Rama to himself, thinking of King Dasa-ratha's nights in the seraglio, "how he must have suffered." And Rama, then and there, made up his mind that never, never, never would he follow in his father's footsteps.

Having made this good resolution, he set about finding a way in which he could keep it. He dismissed the ambassadors and, giving orders for his own departure, he retired to the inner courtyard of Ravan's Palace to avoid the bustle and noise of packing, and to think.

He thought first that he would like to be known to history as "Rama the Chaste" but he remembered Valmiki's tale of Kumar. He next thought that he might make a great study of the laws of his country and produce a code which

would endure for a thousand years, the Code of Rama the Wise: but he remembered the locust and tempered his ambitions. He next thought of half a dozen ways that would help him to rise above his baser nature, but none of the six would have passed Valmiki's scrutiny.

"Yet," said Rama, pacing the courtyard, "even Valmiki says that he does not know everything. I feel that there must be some way in which a man can elevate his spirit which he has overlooked. Are we like animals, chained to our appetites? I cannot believe it."

At this moment an official of his retinue came into the courtyard and, bowing profoundly, asked if there was anything which His Majesty especially wished to preserve in Ravan's Palace—any artistic object, furniture, statue, or so forth. If not, then, said the official, perhaps His Majesty would condescend to indicate at which hour the customary looting could begin.

Rama glanced round the ugly little courtyard, the lumpish statues and the squat columns. He remembered with a shudder the gilt bedroom in which he had slept with Sita the night before.

"No," he said, "there is nothing. King Ravan's taste was even worse than that of my father." As he said this, a splendid and most elevated idea struck him, with which he was so enamoured that he forgot to set the hour for looting, with the result that Ravan's Palace was stripped piecemeal and furtively, without joy, and without conflagration. For this reason Rama was forever after known in Lanka as The Merciful.

Rama did not mention his splendid notion until the immense cavalcade of the Court, the Royal Guard, and the Royal retainers had nearly completed its journey towards Ayoda. The city came into sight at twilight, and Rama gave orders that camp should be pitched for the night, so that his entry into his patrimony could take place in the full light of day.

A silken tent was put up for Rama and Sita, and by

Rama's orders the front hangings were raised on ebony poles so that the city lay before them as they ate and drank. He summoned Valmiki to join him.

When Sita retired to rest from the fatigues of the day, Rama stayed and talked to Valmiki for some time, reviewing their experiences together and so passing on to what he would do in the future.

"Looking at the city of my birth again," he said, "brings back to me something of my youth—the time, that is, before I had the melancholy advantage of your wisdom. I think that there was something touching in my faith in the goodness of mankind, and in noble ideas. I regret that it is gone. But there is still something left. Your views of the general run of the world may be—indeed are—correct. But there are human spirits which rise above it and I think you are inclined to forget them—a strange thing, since you are a poet. I mean, of course, artists. These are the men who can elevate our spirits. These are the men who can show us a finer world than the one which you delineate. The wise man, it seems to me, will take refuge from the deficiencies of his fellow men by the cultivation of his sensibilities, his taste, his appreciation of the finest products of the human genius. This is what I mean to do. I shall beautify Ayoda with the most exquisite works of art that I can find. I shall raise harmonious buildings that will be a benison to the weary soul. And when the world becomes too much like what you say it is, I shall shut myself up in my cabinet and bury myself in beauty. In this way I shall not have held my early ideals quite in vain. I have given a great deal of thought to the matter, and I think that my solution is the wisest, perhaps the only one, for a sensible man. You are, I see," said Rama, "smiling. If I am wrong in my plans, please correct me."

"One does not correct kings," said Valmiki. "But your Majesty's vision of the future reminded me of the experiences of one of the finest geniuses in creation of works of art that our country has ever known. But Your Majesty

will have more important things to do from now on than to listen to my tales."

"I shall always be glad," said Rama, "to hear of the experiences of a genius, especially in the creative arts. Please tell me your tale."

"Well, then, as Your Majesty commands. But, Rama," said Valmiki, taking Rama's hand and pressing it, "it must be the last. I am no courtier, and I have my poem to finish. I shall go with you into Ayoda—it is a long time since I have seen it—but then I shall ask your permission to leave."

"I shall give it very reluctantly," said Rama, and pressed Valmiki's hand in return. "But let me hear your tale, the last, if it must be so."

Valmiki drank deeply from his sherbet, looked into the crystal bowl for a moment and then began the Tale of the Stone Woman.

Young Balan (Valmiki said) was a genius, but apart from that his parents and his friends had nothing against him. His father and all his friends were stone-masons. For ten years they had been engaged upon the building of a temple. This temple was in the shape of a small pyramid with a flat top and four sides. Each of the four sides was divided into eight layers and each of the eight layers had a hundred sculptures of gods, goddesses, devils, and attendants. The carvings were not very good because the stone-masons were not very talented: but the finished temple would have been harmonious, if rather dull, had it not been for Balan. When Balan had begun to carve he had tried to be as bad as his elders and betters. But although he shed many tears and was often thrashed, he was always the best carver of them all.

The stone-masons were, by and large, coarse men, very ready with their fists, and young Balan led a miserable life. Fortunately, the master-mason could recognise genius when he saw it and when he saw it he knew what to do.

One day at sunset he told Balan to wait behind when the others went home, and in the twilight, standing in front of

the small leopard which the boy had been carving, he spoke to the genius in this kindly manner:

"Balan, that is a very good leopard."

Balan looked up at him in surprise.

"Do you think so, sir?"

"I do. I think it is the best carving of a leopard I have ever seen."

"That you've *ever* seen, sir?" said Balan, and tears of pleasure wetted his eyelashes.

"Yes, and I've seen more carving than most."

"Oh, yes, sir. You've seen everything."

"But I've never seen a leopard as good as that. Not anywhere. For instance, there are fifteen leopards already carved on this temple. Can you show me one as good as yours?"

Balan did not know what to answer. He assumed in any case that no answer was expected because the twilight was now so dim that neither his nor anybody else's carvings could be seen. But this did not trouble the master-mason, who went on admiring Balan's and disparaging the others as though it were broad daylight. The master-mason was proud of being able to handle his men. He took trouble. He took so much trouble with Balan that at last the boy gained enough confidence to agree that his leopard, if not better, was certainly different, "because, sir," he explained, "I went to the palace gardens and looked at the leopard that the Prince has got in a cage there and I don't think the others have done that or at least if they did it was a long time ago. When leopards," he added, politely, "might have been different."

"Different," said the master-mason. "Different. That's the very word I have been looking for. Your leopard is different."

"Yes," said Balan, gaining even more confidence.

"So of course it spoils the design," said the master-mason, casually. "Of course it does and of course everybody says it does, and of course the Prince will say it does when he

sees it and you'll get into trouble. People do not understand genius when they see it."

"No," said Balan, not quite so sure of himself.

"No," agreed the master-mason, "so that's why tomorrow I'm going to take you off the outside and put you to work on a corner of the walls inside where you can be as different as you like."

"Oh thank you, sir," said Balan, and he made to kiss the master-mason's feet, but the man stopped him, patted his shoulder and left. Balan, his pulses racing with pleasure, turned to his leopard. He stroked it fondly with the tips of his fingers. It was now quite dark.

So was the corner in which, next morning, he was put to work. It was one of the two corners which faced the altar. Therefore anybody who came into the temple in the right frame of mind would keep the back of his head towards it. When he left he would perhaps see it better, but only if he threw back his head and strained his eyes until they watered. The master-mason led Balan to this corner, helped him up the bamboo scaffolding, gave him an oil lamp and said:

"Now my boy, I'm not going to try to tell a genius like you what you should carve on the stone there in front of you. You can carve exactly what you please. And if anybody tries to stop you, just you tell me and I'll have two words with him that he won't forget."

"Thank you," said Balan, and when his patron and protector had left him, he burst into tears. The violence of his weeping surprised him and he said aloud between his sobs:

"I didn't know that anybody could be so miserable as I am." In the next instant he told himself that he didn't know that anybody could be so frightened, for a voice that was neither human nor animal but more unpleasant than either had said mockingly in his ear:

"Ha!"

Balan knew that it was a devil and hastily began to pray.

"What's that you're muttering?" said the voice, sharply,

and once more it came from the empty air next to Balan's ear.

"I'm praying that if you're a devil you'll go away," said Balan.

"I'm not a devil," said the voice. "Do you know what I really am?"

"No," whispered Balan.

"Guess," said the voice, with a most unpleasant tone of mockery.

From the sound of the voice (which was all Balan had to go by) it seemed to Balan that he was being addressed by a very old and bronchial dog in the worst of tempers. But Balan thought it wiser not to say so. He therefore stayed silent, except for a single sob that remained from his storm of tears.

"Hold up your lamp, boy!"

Balan obeyed, trembling so much that the small flame was all but blown out. When it had steadied again, Balan saw that at the other end of the platform on which he stood sat an aged man who even in the flickering light of the lamp looked extremely dirty.

"Good morning, brother genius," the voice spoke in Balan's ear: but the lips of the old man moved with the words. Balan glanced to his right and back to the old man. "It's the echo from the shell," said the voice. "Fancy a young genius like you not guessing that," said the old man, sarcastically, and Balan saw that the corner near which he stood was carved into the shape of a large shell with ribs of the greatest delicacy.

"Come here," said the old man.

Balan cautiously edged his way along the platform.

"Look at that," said the old man, and taking the boy's wrists between fingers caked with dirt and stone dust, the old man drew the lamp towards the wall.

Balan saw what he took to be a growing flower and then beside it another, and then another. Balan touched them with his fingers and found that they were of stone.

"One hundred and eighty seven of them," said the old man. "One for every week that I've squatted up here like a monkey on a mango tree. I can do them with my eyes shut now. I don't even trouble to light my lamp. It saves the money that would go in oil. What d'you think of them? If you don't like 'em, don't tell me because I don't want to hear."

"But I do like them," said Balan. "They're wonderful. I wish I could carve like that."

"Well," said the old man, "since that son of a diseased she-buffalo has stuck you up here on this perch with me, you probably can."

An hour later, when the old man had told enough of his life story to convince Balan that the master-mason was a scoundrel, Balan said:

"I shall run away."

"I've done that," said the old man.

"I shall run away to another country."

"I've done that," said the old man.

"And when I get there I shall go to the first place where they're building and I shall take a bit of stone and carve it and then I shall say to the master-mason, 'Give me some work.' "

"I've done that too," said the old man.

"And what did they say?" asked Balan.

"They said that they didn't want any dirty foreigners teaching them their business."

"That was because they were ignorant," said Balan.

"Yes," replied the old man. "Then somebody on the top scaffold dropped a mallet and it hit me on the head. That was because they were ignorant too."

"I see," said Balan. "So you came back here."

"I had to eat."

Balan sighed.

"And so have you," said the old man, "so you'd better get to work."

"What shall I carve?" said Balan.

"Anything you like," said the old man. "Nobody but me will ever see it."

"Well then, what would you like?" said Balan, for he had conceived a great respect for the old man, the flowers being so wonderfully well carved.

"Want to know?" said the old man, picking his ear and glancing at Balan out of the corner of his eye.

"Yes, master."

"I'd like a woman," said the old man, and smacked his lips.

"You mean you'd like me to carve a woman?" said Balan.

"That's right. Never could do them myself. Do one standing on that shell. No. Sitting. No. Standing. Well, anyway you like so long as she's a woman."

"I don't know that I can," said Balan. "I've only studied leopards. I don't think I've really looked at a woman."

"No?" said the old man, squeaking with surprise. "That's a funny thing. As for me, I don't think I've ever looked at anything else. I'll tell you what they look like. First," said the old man, and raising a grimy and descriptive finger, he catalogued their charms.

When he had done, Balan said:

"Well, sir, perhaps I'd better have a look for myself."

"Do," said the old man, croaking affably, "do. Mebbe you'll see something I've missed."

"I don't think so," said Balan, and edging away to his end of the scaffolding, he busied himself for the rest of the day taking measurements of the stones and chalking out a site for his carving.

That evening, and for many evenings afterwards, he went to the well to study the women drawing water. Next morning, and for interminable mornings afterwards, he carved in his corner. The old man took so much interest in the progress of the work (although he was often impatient) that he brought his own lamp and oil, and all but gave up

carving his flowers. Balan still thought him a great artist, but he had learned that if you wish to admire great artists, it is better not to listen to their conversation, this being one of the reasons why great artists are admired much more when they are dead.

•

Balan had scarcely finished carving the last of the statue's toes when, one day towards the beginning of the rains, he and the old man were turned out of the temple. Their scaffold was torn down, and they were set to the ignominious task of seeing that there was not a single loose stone on the whole of the path from the doorway of the temple to the grand west portal of the Prince's palace. This was not because they had done anything wrong--nobody could recall what they had been doing—but because the Prince had decided to visit the temple and observe the progress of the work. This caused much anxious bustle because the Prince was a man of great taste who thought sufficiently highly of artists to cut off their heads when they were very bad; and when they were very good, to tell them so. This was considered most condescending on His Highness' part and every artist in the Kingdom aimed to please him.

On the day of the visit, everybody who had taken any part in the building of the temple were assembled in front of it. In the first row were the Prince's counsellors and advisors who had said that it was quite unnecessary to waste money building a temple but who, when the Prince had ordered work to start, had been broad-minded enough to raise no objection. Behind them came the Royal Suppliers, who had found stone (which was underneath their feet) and workmen (who daily stood in the middle of the market-place in search of work). Behind these came the architects of whom there were eight, each of whom had drawn up a design for the building and had had it turned down by the Prince, thus proving that the Prince was eight times as good as any architect in the Kingdom. Behind these stood the master-mason who had built the temple according to

the Prince's instructions, save that he had put in a few tricks of the trade to ensure that it did not fall down: then, at a considerable distance came the men who had built the temple, their sons, their relatives and friends: behind these stood Balan and the old man. Behind Balan and the old man was nobody because from so far away nothing could be seen at all.

When the Prince arrived the people in the front rows saw a tall man without much hair on his head, who had thin but delicately shaped lips, a fine curved nose that was a little wrinkled up at the nostrils, and eyes that were half-closed as though from insupportable weariness. He was dressed in the height of a foreign fashion that consisted of shawls draped around the upper part of his body, the whole elegantly caught in at the waist with a belt made of gold tissue sprinkled with little round pieces of looking-glass. The prince walked on gold sandals under a silk umbrella and the bystanders bowed to the ground and looked at him through their fingers.

The Prince tilted back his head and looked at the façade of the temple. It was forty-six feet high and it was carved with seven hundred figures.

The Prince said:

"Charming." He ran his eyes over the seven hundred figures and his expression was that of a man looking at a litter of puppies.

"Clumsy in places, but charming," he said.

Everyone took his fingers away from his eyes, straightened his back, looked at the forty-six-foot-high temple as though it were a litter of puppies and said: "It is charming."

Speaking to the man who bore his umbrella, the Prince said:

"It is not a masterpiece, but then, we did not expect masterpieces from our local talent." He then went inside and was immediately followed there by the Chief Brahmin and some seventy lesser Brahmins, all chanting.

The Prince's last remark had been spoken quietly and this caused confusion among the spectators. Some heard the word "masterpiece" and therefore gazed at the temple transfixed, drawing in little breaths of astonishment. Others heard the words, "We did not expect masterpieces from our local talent," and these were beaming upon the master-masons: while others heard exactly what the Prince had said and therefore looked contemptuous and amused. Since this last is a striking and sobering expression, the others became aware of their mistake, and in due course everybody managed to look contemptuous and amused, except the stone-masons. Balan and the old man had no noteworthy expression on their faces at all because they had heard nothing and seen nothing except the tip of the Prince's honorific umbrella.

By the time that everybody outside had assumed the right expression, the priests inside had got well launched into the ritual of blessing the temple: a long affair in any circumstances, but particularly now, since the Chief Brahmin had the Prince at his mercy, and the Prince a year ago in the Palace, had called him a prosy old fool. The Chief Brahmin therefore spun out the prayers and scattered the holy water with the deliberation of a man distributing the last remaining drink to a caravan lost in a desert. The Prince sat upon a carpet in a devout posture, and yawned.

The Prince looked up and round the hollow pyramid of the temple but could make out nothing, since the ritual lamps of the Brahmins scarcely carried beyond the altar. The Prince yawned again and began dressing himself in another foreign fashion, item by item, in his mind's eye. This was a favourite device of his to pass away the time, and in following it out, he began to play with his sash. The mirrors on the sash threw reflections. One of these fell straight on the face of the Chief Brahmin, putting his chanting out of beat in a manner which the Prince found amusing. The Prince now began to aim one of the mirrors with more accuracy, but the Chief Brahmin, glancing at him as he did

so, the Prince pretended to be throwing the reflection on the walls.

Thus, quiveringly alive in the beam of the mirror, Balan's statue burst upon the astonished Prince.

V

The Tale of the Stone Woman concluded

WHEN the ceremony was over the Prince came out of the Temple. His brows were drawn together, his eyes flashed, and his lips were tight with anger. He spoke sharply to a Chamberlain, who spoke irritably to the front rank of the crowd, who spoke furiously wth one another. After a moment, the master-mason strode towards Balan and seized him by the shoulder.

"This is the scoundrel," he said, and gave Balan a vigorous push. "This is the scoundrel who carved the woman. Beg pardon at His Highness' feet and may he have mercy on you."

Balan could now see the Prince quite clearly, for the crowd had parted to leave a lane for him. He saw not only the Prince, but also the Executioner who stood by his side.

The stone-mason gave him a second push and Balan ran unsteadily down the lane until he reached the Prince, when he flung himself face downwards in the dust a few inches from the Prince's golden sandals. He heard the Prince's voice above him.

"Is this true?" the Prince said. "Is it true that you carved the woman?"

Balan bobbed his head up and down in the dust.

"I mean the woman in the north-east corner," said the Prince.

Balan bobbed his head again.

"How old are you?"

"Eighteen, Sire."

"Did anybody help you?"

"No, Sire."

"It is a masterpiece. What is your name?"

Balan, lifting his mouth from the dust, told the Prince's shapely ankles his name.

"It is I who should be grovelling on the ground before you," said the Prince's voice. Balan lifted his eyes to the Prince's knees. The Prince went on, "However, in the circumstances, your present position is to be preferred. Look up," Balan did so. The Prince's expression was ferocious.

"Do not take any notice of the way I look," the Prince went on. "If they thought I liked your sculpture I would never have found out who did it. I should have been told it was done by the son of my superintendent of works who has not enough talent to carve a pat of butter. Get down on the ground again."

Balan, his blood racing with pleasure, obeyed.

"I want to talk to you. Can you hear me?"

"Yes, Sire."

"When I tell you to get up, rise and follow the Executioner. You understand?"

"Yes, Sire."

"Look as though you are going to have your head cut off."

"Yes, Sire."

Balan raised his eyes to the Prince's ankles again.

"Sire."

"What now?"

"How does a person look who's going to have his head cut off?"

"There speaks the true artist," said the Prince. "A person in these parts who is going to have his head cut off looks, if possible, even more stupid that he does in normal circumstances. I find it very disappointing. You would think that the prospect of being decapitated would sharpen their wits a little, but it doesn't. Now, be quiet and do as I told you. I cannot keep this expression any longer. It is making my face ache and I shall develop lines on my forehead. Rise!"

"He deserves it," said the crowd, as the Prince, his um-

brella bearer, the Executioner, and an expressionless but dusty Balan slowly walked away.

When they arrived at the Palace, the Prince questioned Balan again, and in private, nor was he quite satisfied that Balan was the sculptor of the masterpiece until Balan had modelled a piece of clay into the shape of an animal. The animal that Balan chose to model was a leopard, and when the Prince had done admiring it, Balan explained how he had looked at the leopards in the Palace gardens and carved what he saw.

"Do you always carve what you see?" asked the Prince.

"Always, Sire."

"Did you see that woman?"

Balan, thinking of the hours he had spent by the well, said:

"Yes."

This answer put him into the most desperate peril, but not immediately. First, the temple was surrounded by soldiers every evening: the soldiers built a platform inside the temple and for ten evenings in succession the Prince climbed the scaffolding and while the officers of the army held flaming torches, the Prince gazed at the masterpiece.

He admired the lines, the planes, the pose, and the rhythm of Balan's sculpture until Balan's head swelled with pride and he stopped adding "Sire" to the end of every sentence when he spoke to His Highness. During these ten days Balan lived luxuriously in the Palace and was given everything that he desired, except money.

Then on the eleventh day the Prince said to him:

"I have decided four things. First, I shall reward you with a gold chain, the title of Sculptor to the Court, and a suite of rooms in the west wing to be yours as long as you live."

Balan bowed, by no means to the ground, but respectfully.

"Second," said the Prince, "I have decided that these honours shall be showered on you on the day that you

bring here before me the woman you studied as a model of your sculpture and," went on the Prince as Balan began to protest, "thirdly I have decided to marry her: that is, if she is exactly, and in all respects, the same as your wonderful sculpture. Fourthly, if she is not, I shall cut off your head as an impostor, even if you carve me a whole menagerie of leopards. That is all. Have you anything to say?"

But Balan had nothing to say at all for he lay at His Highness' feet insensible.

The Prince gave Balan seven days in which to produce the royal bride. A hundred times on each of those seven days Balan cursed his genius: although he spent hours at the well, he could find no one woman who looked like his sculpture. Some had the eyes, many had the mouth, a few had the bosom and two had the hips. But short of cutting the women up and sticking them together again—which was what he had done in his mind's eye when he carved the statue—there was no way of meeting the Prince's demand.

On the sixth day he had chosen a girl in desperation and by denying the plain evidence of his eyes, he had told himself that she would do. He had gone to the Prince with as much courage as he could muster and he had begun to say the woman's name: but the sight of the Prince's discriminating eyes, the sight of the Prince's fastidious nostrils, and the knowledge that in matters of art the Prince was notoriously no fool had betrayed him. He had backed out of His Highness' presence, confused, trembling, and almost as bloodless as when he swooned away.

The Prince affected to notice nothing of all this. But when Balan reached the door in his backward progress, the Prince asked his chamberlain in a loud voice to tell him the date.

The rest of this sixth day of his allotted seven, Balan spent in wandering through the town looking at women in a manner so distracted that they drew their head-coverings more closely about their faces and trotted rapidly away from

his neighbourhood with indignant clatterings of their silver anklets. Thus occupied, and scarcely knowing what path he took, he drew near the temple in which his misfortune had begun. He was seized with a great desire to tell his troubles to someone, and, seeing the temple, he remembered the old man with dirty hands who had been his partner on the scaffold. It seemed to Balan that this old man was sufficiently obscure and friendless to be safe with Balan's secret. He hurried towards the temple.

While nobody in the town knew just how Balan had contrived to escape (as it seemed) his fate, anybody with eyes could see that Balan still carried his head on his shoulders. Besides, he wore a Court robe, a sure sign of the Prince's favour. Therefore, when the master-mason saw Balan approaching the temple, he scrambled down from his scaffold, ran towards him, and made the young man a profound salutation

"Ah," said Balan, with some irritation, "my old master. I was looking for the man who used to work with me inside."

"His Highness wants him?" said the master-mason, bowing again.

"No," said Balan. "No, not at all. I—I wanted to discuss something with him myself."

"Of course, of course," said the master-mason. "Nothing could be more natural. Unfortunately he has been sent away." He bowed a third time and as he did so he could not help admiring his own knowledge of how to handle men. Anybody else he reflected, would have made the mistake of treating Balan as an old friend. But not the master mason.

"Is there any way in which I could help you?" said the master-mason.

"Yes," said Balan. "I've told you. I want to speak to the old man. You can tell me where he is."

"Certainly, certainly," said the master-mason. He permitted himself just the least touch of familiarity. "His

Highness was very complimentary to me about the statue which took his fancy. But of course I insisted that it was you who carved it, not me."

"That was kind of you," said Balan, looking about him impatiently.

"It was no more than the truth. As I told His Highness, my part in it was merely to guide your hand with my experience and to encourage you to go on when the difficulties got too much for you. His Highness . . ."

But at this moment Balan saw the old man sitting cross-legged on the ground a hundred yards away, smoothing a large stone with his chisel. He made his excuses very hurriedly to the master-mason, who, with all the breeding in the world, said that he fully understood. He said that he hoped that Balan would pay him a visit tomorrow.

At this word Balan went pale.

"Or the day after tomorrow," said the mason, with great tact; at which Balan said, seizing his hands emotionally:

"Oh yes. Yes, so do I. I do hope we shall meet the day after tomorrow."

As the stone-mason watched Balan make his way towards the old man, he smiled. There was no doubt, he told himself, that he knew how to handle men.

The old man had grown, if anything, dirtier since Balan had last seen him and his voice had become more cracked. When Balan had seated himself beside him (for the old man gave him no greeting) the old man said:

"They don't let me work inside any more. Know why?"

"No."

"Because they think the smell of me might annoy your fancy friend."

"You mean His Highness?"

The old man, for an answer, sent chips from the stone flying in Balan's direction.

"So they put me on this," he croaked. "To what," he

said, "do I owe my promotion? Your pull at Court, I suppose?" The old man spat.

Balan with tears in his eyes said:

"Don't be angry with me. And I haven't got any pull at Court. In fact, I'm in dreadful trouble."

The old man glanced at his face and then, laying down his chisel, said:

"Tell me, my boy."

"How long have you got to find her?" asked the old man, when Balan had finished.

"Till tomorrow morning," said Balan, and he stared at the old man with wide open eyes, picturing the morning, the Executioner, his sword, and his own head rolling across the Prince's marble floor.

"Well, that's plenty of time," said the old man. "I know she's in the village because I saw her on the road not an hour ago. Fancy little chit," said the old man, with a salacious grin. "If you go now you'll catch her by the well, I shouldn't wonder."

"Catch who?" asked Balan.

"The woman you're looking for."

"But she doesn't exist," said Balan.

"Oho, yes she does," said the old man. "She's the one we all call Lotus Blossom."

"*Lotus* Blossom?" said Balan in a shocked voice, for she was the town's most notorious young woman.

"Yes," said the old man. "Though she's pretty well in full bloom by now, eh?" He chuckled enormously at his own joke until he had to stop for a fit of coughing.

"But she's nothing like my statue," said Balan.

"Look," said the old man, wagging a dirty finger at him. "You're maybe a genius but you don't know anything about life."

"That's true."

"Whereas me," said the old man, "I *am* a genius and I know a sight too much about life. So just you go and tell

Lotus Blossom to have a talk with me and after that you take her to the Prince. It'll be all right, I promise you."

"But what a gamble," said Balan, almost crying with anxiety.

"Better a gamble than a dead certainty," said the old man, and he made a chopping gesture with his unwashed hand that made Balan's blood stand still in his veins.

Balan went to the well. He did not have to search for Lotus Blossom. The difficulty for any well-dressed young man in her vicinity was to avoid her. She cast Balan a languorous look and walked past him in a provocative manner. Balan coughed. She stopped. He looked furtively to left and right and delivered his message.

Lotus Blossom listened. Balan asked her if she had understood. She lowered her eyelids slowly looking sideways up at him. In her usual daily run this expression spoke volumes. Balan, in the circumstances, found it uninformative. But she sinuously walked away and since she was going, however loiteringly, in the direction of the temple, Balan took it that she had grasped his message. He looked after her and sighed. She was not even the same height as his statue.

In the cool of the evening Balam presented Lotus Blossom to the Prince. His knees shook but he managed to keep control of his voice as he told the Prince of his final success in finding his model. He waved his hand towards Lotus Blossom, who stood beside him swathed from head to foot in innumerable gauzes.

"Unveil," the Prince commanded.

"Highness," said Balan, "the lady requests that she be seen by the same light as you saw my statue: namely, she asks for lamps and a darkened room."

"Æsthetically," said the Prince, "there is much to be said for such a course. Come, my dear," he said, endeavouring

to pierce with his eager eye the wrappings about her, "let us go to an inner apartment."

Curving rhythmically, Lotus Blossom followed the Prince into a small but restfully appointed room in which the Prince had his day bed.

Attendants drew the curtains; servants brought lamps. When they were lit, the Prince clapped his hands and everyone save Lotus Blossom and the Prince withdrew.

"Come, my dear," said the Prince, and drew her down on to the bed. As she slowly sank into a sitting position, Lotus Blossom deftly dropped an aromatic pastille into the nearest lamp.

The Prince remembered his reputation. He made some remarks about sculpture, but they were perfunctory. "Now, my dear," he said.

Lotus Blossom leaned towards him, kissed him, lowered her eyelids and lengthily unveiled.

As Balan knew, there were innumerable differences between her torso and that of his statue. The Prince passed them over, noting only one. He observed, with rapturous delight, that Lotus Blossom was by no means made of stone.

Balan waited in an agony of suspense until the Prince sent out for an elaborate supper for two. Balan waited on till midnight, more puzzled than anxious, until the Prince sent out for sherbets and his sleeping gown. Then Balan went to bed and slept until next morning, but with some very bad dreams. A knock on his door brought him bounding out of bed, his fingers feeling his throat. The door opened to admit a gigantic negro slave bearing a scimitar.

Its hilt was incrusted with precious stones. Turning this rich hilt towards Balan, the negro slave thrust it into Balan's trembling hands. A bustle at the door heralded a Court official who, out of breath with running, read from a vellum scroll the announcement that His Highness had raised Balan, at six o'clock that very morning, from the rank of Sculptor

to the Court to the rank of Sculptor Extraordinary, with the right to bear arms, the rank of a nobleman, and a pension for life.

Once more, Balan fainted dead away.

Some weeks later Balan and the old man were taking their ease in the garden enclosure of Balan's palace suite. The old man was now Advisory Assistant to the Sculptor Extraordinary and he too had a pension. He also had an official robe of white damask, in which despite a thorough scrubbing by the Palace attendants, he managed to look dirtier than ever.

"How did you know?" asked Balan, "that His Highness' celebrated good taste for artistic things had—well—it's other side?"

"How?" said the old man. "I'll tell you something, and see that you always bear it in mind. Art is long, me boy, but a touch of Mother Nature goes a dam' sight further."

"Yes," said Balan, and remained silent until it was time to go to an official reception.

He scarcely touched a chisel again till the day of his death forty years later, for he was too busy being an officially acknowledged genius.

VI

The Ordeal of Chastity

DURING the whole length of the festivities which greeted Rama's return to Ayoda (with his army accompanying him to add conviction to the citizens' rejoicings) Sita's title of Most Faithful Wife had the desired effect of repressing gossip. Barat met his brother a mile from the gates, dressed in plain white, and in a lengthy speech insisted that he accepted the throne only as a regent. Rama and he went on together in the same chariot and the acclamations of the citizens were frantic. Flowers were rained upon Sita, and some of them fell upon Valmiki who rode in her train, disguised as a Royal tutor, for he feared his enemies, the Brahmins, even under royal protection.

At the gateway the procession was witnessed by a stately if coarse-featured lady who was dressed for travelling, and whose sumptuous caravan waited in a side alley. This was Mantara, once a nurse, then the Lady Mantara, and now a rich old woman with a safe conduct from the clement Rama.

When she heard the citizens near her shout Sita's new title, she said:

"Most chaste, eh? When I was a girl, a woman who'd lived in the house of another man had a little test to pass before she was called that. Some of 'em passed it, I don't deny, or so it's said. But most of them were done to a turn."

The citizens laughed, and Mantara, the procession over, called her camels and went on her way, wicked, malicious, exposed, disgraced, and the owner of a small fortune in State jewels. Thus nemesis, if not bankruptcy, overtakes the wrong doer in the end.

The rejoicings lasted three days. At the end of this period the citizens, reluctant to return to the daily round, looked about them for other entertainment. It was then that the

words of Mantara bore fruit. The citizens, in a loyal address to their beloved ruler, asked that he put his wife on a pile of inflammable wood and ignite it. If she was burned it would prove that she had been unchaste. If she was not burned (and they were loyally sure she would not be) it would prove that she was chaste. The Brahmins, to a man, applauded the idea which they said had the sanction of religion and ancient custom.

Rama received the address in full state. In the days before his exile he would have been enraged, horrified, and indignant. He would have denounced the custom as barbarous and the citizens as ghouls. Now he dismissed them with little gifts, and sent for Valmiki.

Valmiki, in turn, sent for the King's astrologer.

The King's astrologer listened to Valmiki and said that it could certainly be done but the matter would take time. He would have to make experiments, first with an unchaste woman and then with a chaste one. In these matters one had to proceed step by step. He would need apparatus.

Rama, who was present, had progressed sufficiently in the art of government to tell the astrologer that his apparatus was ready and waiting. Striking a gong, he called for someone to lead the astrologer to his new laboratory. The astrologer was less surprised than Rama had hoped when after a moment the two torturers, grown rather fatter but no less menacing, stood ready in the doorway.

The astrologer sighed and turned to Valmiki.

"It is called Egyptian Fire," he said. "It is used by the priests of Anubis to produce miracles. I can make enough of it for your purpose in twenty-four hours.

The next day but one the great square in front of the temple was packed with citizens standing shoulder to shoulder, so many that the soldiers could barely keep them clear of the pyre which had been built in the middle. It was an immense platform of wood, with two wall-like heaps of lighter wood

running its entire length, leaving between them a narrow pathway.

At noon Rama took up his station on the temple steps under the royal umbrella. At five minutes past noon, chanting was begun by a choir of Brahmins of hymns in praise of chastity, and Rama noticed that one of the best received by the crowd (which joined in) was that written by Kumar.

At half-past twelve Sita came out, dressed in white and surrounded by weeping ladies-in-waiting. Bowing to Rama, she stood in prayer for a moment. Then she mounted the pyre amidst a great silence. As she reached the top, men put torches to the lower levels of the wood, which blazed instantly. Sita now began to walk slowly through the narrow corridor, and this burst into a furious flame and smoke of the most vivid colours. She was immediately lost to sight.

The citizens groaned, but whether Sita was, it seemed unchaste, or whether because they were going to be cheated of seeing her burned to a cinder, they themselves could not have said.

Then, after a considerable interval, Sita emerged, soiled in places, by soot, but otherwise unharmed. As the citizens caught their breath, white doves descended out of the sky and flew around Sita's head.

The enthusiasm of the people knew no bounds except those of the spear-butts of the soldiers who plied them manfully on anyone who approached too near the now historic pyre of chastity.

Drinking cooling sherbet in the Palace afterwards, Rama said to Sita:

"I hope you were not frightened."

"A little," said Sita, but without agitation. "There was more smoke than I expected from what you told me about the Egyptian Fire."

"You need not have been alarmed," said Rama, "I had fifty guards with buckets of water hidden behind the temple

in case of accidents. But the astrologer did very well. I must reward him. Altogether, it was most impressive."

"Still," said Valmiki, "the fire was only a conjuror's trick. The doves, now, which were my contribution, raised the whole thing to a poetic level."

VII

Envoy

THE next morning, very early so that they might part unobserved, Rama and Valmiki rode to the main gate of Ayoda. Two guards, discreetly armed beneath their cloaks, rode with them, a bag of gold at each of their saddle-bows, the King's gift to his mentor.

The gates had been closed the previous night. The two guards rode forward to awaken the gate-keeper. Rama and Valmiki reined in their horses and waited.

A tipsy citizen who had been spending the night in an unsavoury quarter of the town came lurching round a corner. Seeing two gentlemen on horseback, he pulled himself together, wished them a dignified goodmorning, and went on his way, unsteady in his walk, but with an expression of profound respectability.

Rama and Valmiki watched him go, and then smiled at each other.

The gates opened.

Rama said:

"Now we must part. I shall miss you greatly. I lay awake last night remembering the time we have spent together. I made up my mind to ask you a question. You have shown me how many things are an illusion. But in your way of looking at the world, is there anything that you believe is real?"

Valmiki said:

"Certainly, Rama. There are three things which are real: God, human folly, and laughter. Since the first two pass our comprehension, we must do what we can with the third. And now, we both have work to do. We must say goodbye."

The two men leaned from their horses and for a moment, embraced.

Then Rama rode back to the palace to govern Ayoda, and Valmiki, his guards on either side of him, rode through the gate towards a place of tranquillity in which to finish his story.

THE END

A Note on the Indian Enlightenment

A Note on the Indian Enlightenment

THE *Rámayana* is a poem of twenty-four thousand verses. The first version, now quite buried, was very much shorter. It was written during a wave of philosophic scepticism which is sufficiently remarkable to be called the Indian Enlightenment, a movement which threw doubt on the very foundations of society.

The better to understand how extraordinary this was, let us imagine such a revolt happening in our own times. First we must see what the sceptics would disbelieve; what particular pillars of our own beliefs they would shake; in what way they would scandalise even such intelligent, broad-minded persons as the reader and myself.

To do that we must first determine which things in our own civilisation we take for granted because we believe them to be good. I can best arrive at this by describing a man I met in Corsica.

A few years ago I had retreated for the purpose of quiet reflection to a small village or the warmer side of Corsica. This was the village of Cargèse, which has one hotel and this hotel has only two bedrooms. In the dining-room of this hotel I met a Scandinavian. His name meant nothing to me but he was clearly a man of remarkable capacities. I had been living among a backward tribe in India and we struck up a conversation on the subject of primitive peoples. The Scandinavian was most interested to know if my tribe ate maize. I was able to assure him they did not, at which he lost interest in them. But he kindly expounded for me his own theory about the migration of tribes in the Pacific, in the earlier periods of human history. I was interested by his theory, but astounded at his proof. He maintained that the inhabitants of the Pacific islands had colonised them from South America

by floating across the ocean on a balsa raft. He had built a raft and floated across himself.

Like most brave men Mr. Thor Heyerdahl is serious and practical. While he left me to guess the perils of sailing a raft across the Pacific, he told me of the meticulous organisation behind his adventure. This had begun (if I remember correctly) years before with the help of learned societies. It had involved the transportation of his crew by aeroplane: it called for cinematography and for radio telegraphy: it demanded official contracts with more than one department of more than one government: and it naturally had ties with the major news journals of the world. The danger, the vision, the courage, and the glory were those of one man and his chosen companions; but his vision brought into play a vast social apparatus: and not the least striking thing about the Kon-Tiki expedition was that this apparatus had been turned for the first time after many years of war to the peaceful services of civilisation at its finest. It did not surprise me to learn from Mr. Heyerdahl that he had found this side of his enterprise the most exhausting.

Now if we are proud of anything in our times, I think this is what we most take pride in—this community of civilised men that any of us can call upon, either to assist us to send a letter to friend in the next town or, if we have Mr. Thor Heyerdahl's imagination, tenacity, and powers of organisation, to cross the Pacific on a balsa raft. When we think of Mr. Heyerdahl and his fellow-navigators, we are moved by the picture of a few men in the middle of a limitless sea. But we must not forget that Mr. Heyerdahl's object was not to prove the trip a difficult one, but to show that it was easy enough to have been done first by savages, and that he maintains that he has succeeded. What, then, distinguishes Mr. Heyerdahl from the original savage? In point of courage nothing. In point of culture, everything. The savage did little more than shift his body from one point to another; Mr. Heyerdahl moved half the world, in every sense. He used the skills and the brains of uncounted men who make films,

operate radio, print newspapers, follow the progress of ethnology, chart currents, own libraries, pilot aeroplanes, bank money, and reward brave men. Nothing, of course, can detract from the pioneering merit of his feat; but it is significant of our times that when this highly individual scientist kindly left me his address, I found that it was "The Explorer's *Club*, New York".

We have organised the world. Even if we aim, in the end, to blow the world to pieces, that will still call for a greater organisation than history has ever seen, and we shall no doubt be capable of it.

Now suppose some sceptical thinkers arose amongst us and said, "The whole elaborate organisation is, in our opinion, preposterous nonsense. You are all mistaken. It must be scrapped and we must start again on different lines." Would we have a parallel to the Indian Enlightenment? By no means. We should have merely a few cranks.

Suppose, on the other hand, these sceptics spoke rather differently. Suppose they said: "We have nothing against the elaborate toy which you call civilisation. It is very pretty, especially when all the parts are in working order. We do not suggest for a moment that you pull it to pieces and start anew. We do not suggest that you improve it. We do not suggest you do anything at all. So far as we are concerned our only wish is, with the greatest good-will, never to see your face again. If you are curious to know what we propose to do, we shall endeavour to explain, but not very often. We intend to set about the proper business of a human being which is the improvement of his own soul. In this you cannot join us because you cannot call your souls your own. Since you depend every minute of your existence on everybody, you yourself are nobody. However, we will agree, in parting, that you are a jolly good fellow."

This is a true parallel. It will occur at once to the reader that there is another one. The first Christian monks turned their backs on the greatest civilisation the world had seen in the same way, except that I could not quote the language that

many of them used in doing it because it is not fit to print. They, too, considered Roman civilisation preposterous; they also had no desire to alter it; and they too did not encourage earnest seekers after the light to follow them. St. Jerome, writing to a female admirer, who wished to make a pilgrimage, told her sourly that a visit to Bethlehem was not an absolute essential for holiness, Bethlehem being, at the time of writing, his place of residence.

What is it that caused thinking men at two apices of civilisation, that of Brahminical India and that of Imperial Rome, to dismiss the whole conglomeration from their minds as trash, and *to leave it.* It needs no effort of the imagination to see a man wanting to put civilisation right. We all do. This is called Progress. It is more difficult to understand how a man can hold that the civilisation of which he is a member is so unimportant that it is not worth his trouble to put right even if he knew how it should be done. We cannot even dismiss them as saints. Saints generally aim with holy determination to put things right. If I say, "He is a saint: he does not give a click of his beads whether you or even his own mother burns in Hell or not," does it not conjure up a somewhat confusing picture? So these people are not what you ordinarily call saints, whatever your religion: unless, of course, you are a Hindu, when you will not find it confusing at all.

The best way to avoid confusion in thinking about the ways of human beings is to remember that the number of the ideas that have really moved mankind is very small and most of this small number of ideas are very simple. The difficulty is that you and I have room in our heads for only one or two of these simple ideas at the same time.

For instance: one of the most powerful notions in the history of thought is that of the Devil. Another powerful idea is that of Nature obeying fixed laws. If you believe in Nature obeying fixed laws and I believe in Black Magic, and if we both want to obtain a nugget of gold, you will go

prospecting in some place which your study of the laws of geological action has led you to believe has auriferous rocks. I will put a lump of lead in a basin, and sacrifice a cock at midnight on a bare mountain. You will think me an unsavoury charlatan; I will think you an uninspired fool. Nowadays our friends would expect you to find the gold: in the Middle Ages they would (privately) have put their money on me. Because I cannot see your simple idea and you cannot see mine we shall not only differ in our ways of getting gold, we shall differ about nearly everything under the sun. Since you believe that if you know how Nature works she will do as you bid her, you will be confident that if things are left to you and your co-workers, everything can be made bigger and better and everybody made happier. I, on the other hand, believe in the power of evil and I shall say that men are wicked and nothing will make them better and the fact had best be faced. Your idea may lead you to discover antibiotics or nerve gas: mine can make me a great leader of men. But the two ideas that are the base of our differences can be explained to an intelligent child.

The simple idea that led the first monks to turn their backs on civilisation was Heaven. Heaven was a place much better than Rome. It was obvious that everybody was not going there, but it seemed to the monks that those who did not try with all their might and main were as lacking commonsense as a man who owned a palace but lived in the basement because he could not take the trouble to climb upstairs to bed. Like all men who have made up their minds and have no intention of altering them, their greatest plague was well-meaning admirers who would neither take their advice nor stop asking for it. They therefore retired to remote spots to get to heaven by fasting, praying and hoping in peace and quiet. Yet Heaven is such a simple idea that nobody has troubled to explain what it is, except Dante, who in spite of his majestic poetry, does not convince a single reader that he has been there.

The simple idea which arose in India twenty-five centuries ago and which has shaken Indians and many who are not ever since is that of moral obesity.

If, by the action of some malicious genii, I found that instead of being at my writing-table I was clinging to a trapeze forty feet above an audience at a circus, I would be helpless until I was carried down the ladder by attendants. If the same genii transported the trapeze artist at the same time to my writing-desk and invited him to write about the doctrines of *karma*, *dharma*, *maya*, and *moksha* as I am doing, he would also be at a loss. We both lack the necessary practice. Nobody thinks this remarkable. It is accepted as obvious that some years spent daily at a writing-desk will have given me a knowledge of the elements of self-expression: while some years spent in rehearsals will have given him a knowledge of what, from ignorance of the right technical terms, I shall call the ropes. We are both set in our ways and cannot easily change our rôles.

Now suppose that the genii, having restored us to our desk and circus, decides to have more sport. This time he transports us together into the middle of Africa and presents us with two guns, a faithful servant and a rhinoceros. The rhinoceros charges. I fling down my gun and run for the nearest tree and I am too busy climbing it inexpertly to notice that the faithful servant is under the rhinoceros's feet. The trapeze artist, on the other hand, leaps gracefully aside and with admirable coolness raises his rifle and, unable to miss at such short, if terrifying, range, shoots the animal dead and rescues the servant. Everybody would think this most remarkable. The trapeze artist would have shown bravery and I the white feather. If I pleaded that swinging from a trapeze teaches a man to face danger with steady nerves while writing books is a dangerous occupation only under a totalitarian regime, where authors are taken very seriously, it will be accepted as an excuse. But I shall still be thought a coward. Yet what has caused this difference in

our moral natures if it is not the same thing as that which causes the difference in our skills; namely, what we had practised in the years before?

Since the genii is concerned to prove that it is indeed the same thing he now transports us both to a Buddhist monastery. By this he makes his point and saves my self-respect. After a few days I find a cloistered life perfectly acceptable: the trapeze artist finds it worse than incarceration in an asylum. I do not mind spending most of my day in a cell, since writing is a solitary act. The obligatory prayers, which consist of the same sentiments endlessly repeated in different words, I find a good substitute for the daily newspaper. I do not miss my wife because I am a bachelor. The trapeze artist finds the company of monks strikingly less warm than the company of trapeze artists: he does not know what to do with himself when he is alone except handsprings, which are not encouraged. He is desperate for his wife and his growing and acrobatic family. I am given the saffron robe. He is expelled. He goes back to the circus and I proceed upwards to Nirvana.

At this point the genii has established that both myself and the acrobat are a sort of addition sum of the things we have done before. But the trapeze artist denies this hotly, and so do I. He maintains that he is much more than a performer on a trapeze. He is a good father, a faithful husband, a member of the association of trapezists, a Republican, an Elk, an admirer of Ernest Hemingway's *Death in the Afternoon*, and a taxpayer. I have an equally long list, which I may sum up by saying that to describe me as an author would satisfy nobody but a passport official.

However, we have not proved the genii wrong. All the things which we cite as describing ourselves are again things we have done in the past, and again the genii may say that we are both the mere sum of such actions.

If the trapeze artist and myself are not this—and we are sure that we are something more—then what are we? We are of course two separate arrangements of muscles, veins,

flesh, and bones, his being more efficiently arranged than mine. But that is not what we mean. The question is better put as "*Who* are we?" or, to include the reader, "Who are you?"

One possible answer to this last question is "I know exactly who I am. I am John (or Judith) Smith of Acacia Avenue in such-and-such a town in such-and-such a county. Moreover, I have no taste for Oriental hair-splitting."

This answer has saved a great deal of the world's time, and it is practical in the way that it is practical to put a dog's name and address on its collar if you do not want it to get lost. However, the answer is false. The dog is not Pete: you are not John Smith. Both are names given by people who are not dogs or not you.

To proceed to try to find a true answer to the question is to take the first step in entering the world of the Indian mind. The Indian mind was formed by the sceptical thinkers who, twenty-five centuries ago, decided that the answer to the question was that you are originally something utterly different from anything you are called, or anything you do. However, everything you do is added to what you originally are. After a lifetime of doing you are not yourself at all; you have lost yourself. That is, you have lost your soul; that is, you are damned.

This is the explanation that these thinkers gave of their extraordinary answer:—

When a man eats, some particles of the food he takes remain behind in his body. If he eats too much the food becomes particles of fat and he swells so that he can barely recognise himself as the same man. In the same way, of each act that a man does, part remains with him. If he acts in accordance with his own soul, then he is like the man who eats enough. He will remain himself. But if he acts more than he needs, and more than his soul requires—above all if he acts not from his own soul but because of the desires or passions or prejudices of others—then his soul becomes

covered with the deposit of his acts and grows obese. In the end, it may be smothered and die.

The men who put forward this theory offered a proof of it. The proof is metaphysical. The trouble with a metaphysician, then and now, is that either he explains everything or he explains nothing. He can have no half-measures. The Indian metaphysicians proved their theory by explaining the nature and origin of the Universe. Their arguments have been discussed by metaphysicians down to our own times. But speculation about the Universe can be as idle an occupation as chewing a straw. Much of Indian (and any other) metaphysics is little more than an ingenious postponement of the stage when the philosopher has to admit that he does not know what he is talking about: and since what he is talking about is God Almighty, this admission is never altogether a surprise.

Having demonstrated the nature of the Universe, the metaphysicians among the sceptics went on to prove their theory of the soul by describing the substance of the soul. Since neither they nor anybody since has discovered what the soul is made of, we need not stay to follow their reasoning. The best argument for their theory of moral obesity was that numbers of thoughtful people felt that it hit the truth.

They felt this largely because the sceptics were courageous. Had they said that wicked acts influence the soul for ever afterwards they would have been saying no more than nursemaids do in training children. Instead they argued that all actions corrupt and stifle our spirits, and in the word "all" they necessarily included good acts as well. This is what many people had been long suspecting. They listened to the sceptics with a new respect and when the philosophers were driven into exile by an outraged orthodoxy, they followed them in large numbers. The revolution in thinking had begun, and it is still not finished.

I think that it is still not finished because it seems that there

comes a time in the history of every civilisation when, for the sake of human dignity, men turn their backs on it.

Let us see why this is so.

When Rama was a prince in Ayoda, the life of all the inhabitants from the King downwards was governed by a series of minutely detailed rules. Some of the rules were backed by the law: all of them had the sanction of everybody's sense of good citizenship, and this was more powerful than the law. The lives of any group of human beings can be governed entirely by written laws: but you must first build a prison and lock them up in it. Should you be able to persuade them, however, to want to be good fellows, decent citizens, and respected by all, they will build the prison for themselves. In the first great civilisation of history, of which Rama's story tells, men and women had such a respect for the opinion of their community that they even obeyed a set of rules when privately excreting. This would be incredible, if later, the rules had not been written down in a code which can still be read; and this, in its turn would be comic, if those rules were not still obeyed by millions of respectable Hindus today, which makes it melancholy.

"Bright shining faces, And all in our places"; this was the common aim of Rama's contemporaries, as it must be of any civilised body of men. So far as their places were concerned, they all knew them perfectly. Each person was born into a caste, as we have seen, and this caste had its duties and its privileges. Of these, its duties were the saddest: they employed all the most generous impulses of the human spirit, and regimented them. Compassion became alms giving: courage became military service: religion a drill; and independent thinking became bad manners. From the moment a man rose from his bed till the time he disengaged himself from the systematised embraces of his wife and fell asleep again, his acts were prescribed by a committee, part visibly composed of his neighbours, part invisible, and made up of the watching dead. He could do only what others did, what his forebears had done, or what his spiritual advisors thought

might please the gods. The only way in which he could be sure that he was acting from his own free-will was to commit a crime.

If you feel, reading this, that such a state of affairs is a shame, but it happened in a very distant past, then you will find it interesting to ask yourself the question that the Indian sceptics asked two thousand five hundred years ago. "If I wished at this moment to do one good deed that was quite my own—that had not been taught me by school-masters, or parents, or priests, or books, and which did not spring from my social conscience, what would that good deed be?"

The answer that the sceptics gave was a paradox—but then Indians have never flinched from paradoxes. They said that the only thing you could do was to go off to some place where you could be quite alone, sit down and then do nothing at all.

Their answer brought every respectable element of society about their ears.

The Brahmins, who were responsible for the government of society, asked if these self-styled philosophers were not aware that the gods decreed that man was a social animal and that he could not live alone?

To this they tranquilly replied:

"Our forefathers lived beyond the Hindu Kush where they lived in tents of goats' hair and drank the milk of asses. They were also without the benefit of a highly educated caste of Brahmins to provide them with information about the decrees of the gods. We, their descendants, have progressed. Are we not to progress further? Suppose that we, having learned how to live in peace with at least our nearest neighbours, must now, according to the will of the gods, go on to learn how to live at peace with ourselves?"

Prince Rama, being a young man of good education, deplored these heretical ideas before his exile, but they were in the air of the century. Another prince, heir to a Kingdom

as Rama was, but perhaps less well educ[illegible] was [illegible] day by the sight of a dead body at the [illegible] palace. Realising that he too was mortal, he d[illegible] understand more about himself while he ha[illegible] Following the precepts of the sceptical thi[illegible] from his kingdom leaving his wife and fa[illegible] and went to live in a forest.

Here he decided that whatever he was, [illegible] not a bundle of appetites for food, warm[illegible] pleasure, all of which, to be properly supplied, meant that he would be bound once more to his fellows and again enclosed in the prison of social circumstance from which he had escaped.

He therefore practised the most severe austerities, denying himself all but the minimum of food and sleep, sitting motionless for days on end, praying incessantly, and fighting down fearsome rebellions of the flesh. At the end of six years of this life he found that he knew what he was not—he was not a creature of impulse—but he was no nearer knowing who he was.

He lightened his penances and reduced them to thinking while he sat cross-legged under a tree. Here, after long meditations, he found a way of knowing his own soul and a series of ways by which it could be freed from any contamination by worldly things.

The only contamination which remained with him seems to have been a desire to pass on his discoveries to others. He rapidly gathered a devoted if not very intelligent following, and he expounded his methods of securing detachment from the world. It is not easy to see how he could have preserved his own soul uncontaminated when he, by choice, spent the next forty-three years knocking sublime truths into the heads of disciples and admirers. But his notions were profoundly new and exciting: he was an admirable teacher and, it must not be forgotten, a member of the nobility. He was greatly in demand all over the country. Soon his following grew so great that he was forced to organise it. He set

...ich seekers after release from the world ...ne, in a world of their own. In spite of the Brahmins, these monasteries were filled to ...soon as they were set up. It was no doubt ...ple should seek to release their ties with ...themselves to live cheek by jo...l with them ...rs, but again, it was a paradox which dis- ...s of the time, or subsequently.

...of these monasteries was now, by the nature of things, leading as busy and full life as a modern bishop. His fame continued to grow until, surrounded by weeping disciples, he died. He has been known to history ever since as Gautama Buddha. He was eighty years old at the time of his release from this world and he died from eating too much pork.

The reader may now feel that he is on more familiar ground. Buddha is well known in the West, although it is often forgotten that he was as much a typical Indian as Mohandas Gandhi.

But from the point of view of the sceptics, Buddha was something of a disaster. No sooner had he died than an orthodoxy only slightly less absurd than that of the Brahmins was erected over his teachings. The Brahmins found little difficulty in regaining their hold on men's minds and they maintained it down to modern times.

It was during this second hegemony that they altered Valmiki's poem to suit their purposes. Valmiki was not a philosopher: but it is clear from the bare bones of the story of Rama that he was a sceptical realist. With that in mind, I have retold the story, replacing the Brahminical moralising with some tales of my own.

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5. Distinguish between (a) ohmic resistance, (b) inductive reactance, (c) capacitive reactance, (d) impedance.
6. What is the reactance of a 20 henry choke coil of negligible resistance at 100 cycles?
7. What is the impedance if a resistor of 500 ohms is connected in series with the choke coil in problem 6? What will be the cosine of the angle of lag between the current and the e. m. f. in this circuit?
8. What is the reactance of a one microfarad by-pass condenser at 100 cycles? If it is connected across a 2,000 ohm C-bias resistor, what proportion of the current goes through the resistor and what proportion is in the condenser circuit at this frequency?
9. Give the physical reason for the fact that a condenser has a lower reactance at high frequencies than at low frequencies.
10. From the values in the table of Article 161, plot a curve showing the variation in reactance of an inductor of 30 henries as the frequency is increased from 60 cycles to 100,000 cycles.
11. From the values in the table of Article 164 plot a curve showing the variation in reactance of a condenser of .001 microfarad capacitance. Plot this on the same sheet and to the same scales as the curve in problem 10.
12. What is the impedance of a circuit having a resistance of 10 ohms in series with a capacitance of 100 microfarads and an inductance of 50 henries, if the frequency is 60 cycles?
13. How much current will flow in the circuit in problem 12 if the e. m. f. is 1000 volts?
14. Explain what happens in a series circuit containing inductance and capacitance when resonance occurs.
15. Under what circuit conditions do voltage and current differ in phase? Under what condition is the voltage and current in phase?
16. Explain the fact that a lamp connected in series with a condenser having sufficient capacitance will light up when connected to a 110 volt source of alternating e. m. f. even though the dielectric separating the plates of the condenser is an insulating material.
17. Find the true power, the apparent power, and the power factor for the conditions in question 12. Draw the vector diagram.
18. What must be the inductance of a coil to form a resonant circuit with a condenser of .0005 microfarad capacitance, at a wavelength of 200 meters? At a wavelength of 600 meters?
19. What is an *audio frequency* current? What is a *radio frequency* current?
20. If a fixed inductance of 300 microhenries is used to form a tuned circuit with a variable tuning condenser, what are the maximum and the minimum values of capacitance needed for a tuning

range over the broadcast band from 200 to 600 meters? (Distributed capacitance of the inductor to be neglected.)

21. Why is the voltage appearing across the inductance or condenser in a series resonant circuit, greater than the applied e. m. f.? Explain in detail.
22. Explain what is meant by "gain" in a tuned circuit.
23. What are two effects of increase of resistance in a tuned circuit?
24. What frequency corresponds to 600 meters? To 200 meters?
25. What wavelength corresponds to a frequency of 550 kc?
26. What is meant by an "acceptor circuit"? Draw the circuit diagram for one. Where would you use it?
27. What is meant by a "rejector circuit"? Draw the circuit diagram for one. Where would you use it?
28. Explain the important characteristics of (a) series tuned circuits, (b) parallel tuned circuits.
29. An inductance of 200 microhenries is connected in parallel with a capacitance of .0005 mf. At what frequency will they be in resonance?
30. What is the frequency at which the circuit of Question 12 will be in resonance?

CHAPTER 12

ELECTRIC FILTERS

FILTERS — LOW-PASS FILTERS — T TYPE LOW-PASS FILTER — THE "PI" TYPE LOW-PASS FILTER — DESIGNING T AND "PI" TYPE LOW-PASS FILTERS — SOME APPLICATIONS OF LOW-PASS FILTERS -- HIGH-PASS FILTERS — BAND-PASS FILTERS — DESIGNING OF BAND-PASS FILTERS — THE BAND SUPPRESSION FILTER — GENERAL USES OF FILTERS — REVIEW QUESTIONS.

179. Filters: Generally speaking, a *filter* is a device for separating things of different characteristics from each other. Mechanical filters are commonly used in everyday life. Thus a mechanical filter or screen is used to separate sand from stones, a coffee strainer separates the coffee grounds from the liquid, etc. Similarly, when a circuit contains currents of several frequencies, electrical filters may be used to separate currents of certain frequencies from those of other frequencies. The perfection of the modern a-c electric receivers has resulted in the widespread development and use of electrical filters, both in their power packs and in the radio and audio amplifier systems. Heretofore they were used almost entirely in telephone circuits.

The purpose of the electric filter is not very much different from that of any mechanical filter; it is simply designed to separate currents of different characteristics from each other, i.e., for separating direct from alternating currents, or separating alternating currents of different frequencies from each other. Although the design of some complicated filters involves intricate calculations, the more simple types may be easily understood by the novice.

The action of all types of electrical filters depends upon the following three main principles of alternating current circuits:

(1) *An inductor ("inductance") offers much less resistance or opposition to the passage of direct currents and low frequency currents than it offers to high frequency currents* (see Article 161).

(2) *A condenser ("capacitance") offers much less resistance or opposition to the passage of high frequency currents than to low frequency currents, and stops or "blocks" the flow of direct current altogether* (see Article 166).

(3) *That a "series tuned circuit" offers a low impedance at resonance, and will permit the passage through it of those alternating currents which lie in a narrow band of frequencies near the resonant frequency, and will oppose the flow of currents of all other frequencies* (see Article 173).

(4) *That a "parallel tuned circuit" offers a high impedance at resonance, and opposes the flow of those alternating currents through it which lie in a narrow band of frequencies around the resonant frequency, and will permit the flow of currents of all other frequencies* (see Article 177).

Resistances do not provide any filtering action in themselves, for they impede all currents which pass through them, regardless of frequency. Resistances do have an effect of a different kind upon a filter however. They do not determine which frequencies the filter will pass or impede, but they have an effect upon the sharpness of the filter—they determine whether the dividing line between the frequencies which pass and those which do not is finely drawn, or whether the division between the two is of a more gradual kind. The less the resistance in any filter the sharper will be the dividing line between the frequencies which are let through and those which are blocked, and it is usually desirable to have this division as sharp and clean-cut as possible. There is another factor, also, which affects the sharpness of the "cut-off" of a filter. This will be taken up later.

By proper arrangement of condensers, inductors and tuned circuits therefore, any desired electrical filtering action may be obtained. There are four general classes of filters. The first is the *low-pass filter* (Fig. 118). This is the type designed to pass all frequencies below a pre-determined critical or "cut-off frequency", and substantially reduce or "attenuate" the amplitude of currents of all frequencies above this cut-off frequency. This type of filter will also pass direct current without opposition.

Next comes the *high-pass filter* (Fig. 126). This is the type designed to pass currents of all frequencies above a pre-determined critical or "cut-off" frequency and substantially reduce the amplitude of the currents of all frequencies below this cut-off frequency. In most cases a filter of this type will stop the flow of direct current, as well as that of low-frequency alternating current.

The third is the *band-pass* filter (Fig. 129). This is designed to pass currents of frequencies within a continuous band limited by an upper and lower critical or "cut-off" frequency, and substantially reduce the amplitude of the currents of all frequencies above and below that band. In this case, currents of both the higher and lower frequencies are stopped.

The fourth and last of the general types is the *"band-suppression," "band-elimination"* or *"band-exclusion"* filter (Fig. 131). This is designed to substantially suppress currents of frequencies within a continuous band limited by an upper and lower critical or "cut-off" frequency, and pass currents of all frequencies above and below that band. In this case, cur-

rents of frequencies within the band are opposed or stopped. It is just opposite to the band-pass type.

In all these cases, we consider a direct current to be simply a current of zero frequency. We will now study each of these, together with some of their applications in detail.

180. Low-pass filters: Let us consider first the simple low-pass filter shown at the left of Fig. 118. Notice that an inductor is connected

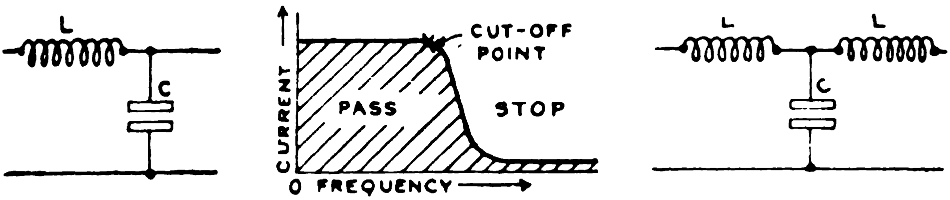


Fig 118—Left Single section of a low-pass filter Middle The frequency-current characteristic of a low-pass filter
Right Single section T-type low-pass filter

in series with the circuit and a condenser is connected across the circuit. If we remember the action of an inductor and a condenser in an a-c circuit, it is easy to understand the action of this arrangement. The low-frequency currents which are to be passed through the circuit find an easy path back and forth through the inductor since the reactance which an inductor offers to low-frequency currents is small ($X_L = 2\pi f L$). These low-frequency currents cannot get in and out of the condenser plates to any great extent since the reactance of a condenser to currents of low frequency is very high $X_C = \dfrac{1}{2\pi f C}$ Therefore low-frequency currents are not appreciably shunted or short-circuited by the condenser across the line.

The high-frequency currents which may also be in the circuit at the same time, find that the inductor offers a high impedance to their flow through the circuit, but that the shunting condenser allows the current to surge back and forth between the plates, (in the electrical circuit) since it offers a low impedance to currents of high frequency. Thus we see that the action of this filter is to offer very little impedance or opposition to low-frequency currents passing through it, but to offer a high impedance to high-frequency currents passing through it, besides partially short-circuiting them across the line.

The result is shown by the graph in Fig. 118. The frequency is plotted along the horizontal axis, increasing toward the right. The current is plotted vertically. This is sometimes called the *transmission curve* of the filter, for it shows how the filter transmits current through the circuit. Notice that at low frequencies the current is strong since the filter passes it easily. The shaded portion of this graph shows the fre-

quency range over which the filter easily passes current. Above the cut-off point the current is low, because the inductor presents a high impedance to the flow of these currents through it, and the condenser plates act as storage reservoirs for these currents during each cycle, thereby shunting them from the load circuit.

The shunting action of a condenser connected across a source of e. m. f. is usually very puzzling to the novice, especially since many confusing and misleading statements concerning it are to be found in popular radio literature. As this important action occurs in many parts of radio transmitters and receivers, as for instance in by-passing radio or audio-frequency currents around a C-bias resistor, or the B-voltage supply device; in by-passing radio-frequency currents in the plate circuit of the detector tube in radio receivers, etc., it will be well for us to obtain a good mental picture of it at this point.

By-passing by means of a condenser is always associated with either alternating, or pulsating direct current. The action is practically the same in each case. Consider the circuit shown at (B) of Fig. 119 which represents the filter circuit of Fig. 118 with an a-c generator or other source of e. m. f. supply connected at the left and a device at the right into which the current from the source is to flow. This load may

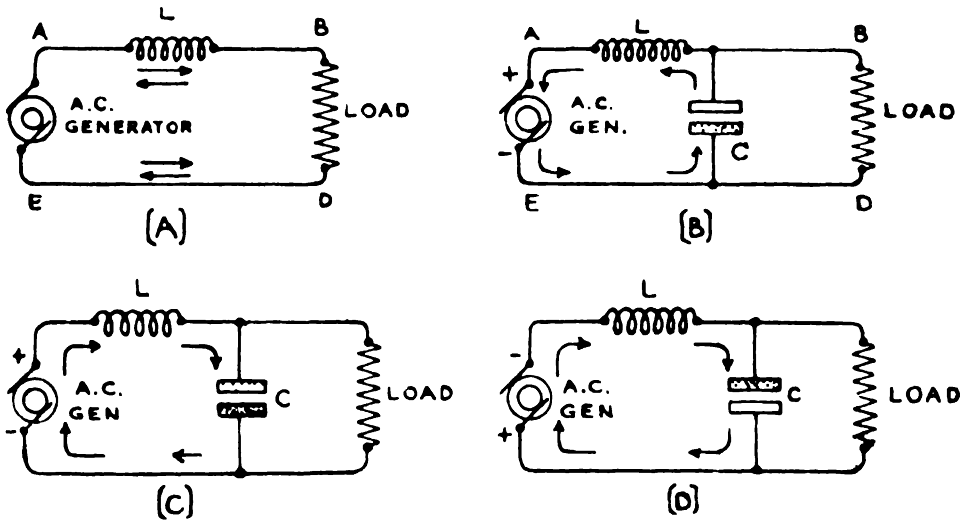


Fig 119 - Illustrating the by-passing action of a condenser across a line.

be simply a resistance as shown. The end of the filter which is connected to the source of e. m. f. is called the "*source*" end. That connected to the load is called the "*load*" end. The e. m. f. of the generator is rapidly alternating, so the current through the circuit is doing likewise as shown by the arrows.

Let us consider the action taking place when the e. m. f. supplied by the generator is at a frequency which is suppressed by the filter. It the condenser were not connected in the circuit, as at (A), the inductor would present a definite impedance or opposition to the flow of current around the circuit, both when it flows in the direction

A-B-D-E and also when in the reverse direction E-D-B-A. At high frequencies this impedance would be high, but some current would always get through the inductor. Therefore the inductor alone would act as a sort of low-pass filter, but imperfectly.

Now if the condenser is connected as shown, during the part of the cycle when terminal A of the generator is positive (as at B) the electrons flow through the circuit in the direction shown by the arrows, (opposite to the direction of current flow). The lower plate of the condenser collects a large portion of the electrons which are being transferred around through the circuit consisting of the upper condenser plate, inductor, and a-c generator (provided the reactance of the load is appreciably larger than that of the condenser so it does not also furnish an appreciable quantity of electrons). If the condenser were not there, as in (A), all of the electrons transferred around the circuit by the e. m. f. of the generator would have to go through the load. Hence it can be seen that the condenser really assists the action of the inductor L, in *reducing* the current flowing through to the load, simply by taking into its plates a large number of the electrons thus *by-passing* them from the load. The larger the capacitance the more electrons it will take in at the high frequencies considered, and hence the greater will be the filtering action. Now when the e. m. f. of the generator has reached its peak value and begins to decrease, the current through the coil tends to decrease, and the collapsing magnetic field induces a self-induced e. m. f. in the coil which tends to keep the electrons flowing into the condenser still in the same direction. When they both die down, the lower plate of the condenser begins to discharge electrons back around through the circuit to the upper plate of the condenser as shown at (C). When the generator e. m. f. reverses, it tends to drive more electrons around to the upper plate as shown at (D) and thus the plate now becomes negatively charged.

When the e. m. f. passes its peak value in this direction the electrons surge around the circuit again in the direction shown at (B). This is repeated over and over again. The inductor of course reduces the number of electrons or current transferred around the circuit in each case, but since the condenser stores some of them each time, less reach the load than would if the condenser were not there. Notice that no electrons or current can actually flow through the condenser, since the dielectric insulates one plate from the other. This is contrary to the misleading statements often made when speaking of this action. Also notice that the condenser will act exactly as described above only when its reactance is very small compared to the reactance of the load it is shunting. If the reactance of the load were equal to that of the condenser at the particular frequency being considered, the latter would only exert half as much filtering action since now half of the transferred electrons would go into the condenser and half would go directly through the load. It is for this reason that the load impedance should preferably bear a definite relation to the impedance of the filter. This will be discussed in Art. 183. The condenser and inductor really form a series circuit across the source of e. m. f.

181. T-type low-pass filter: The single filter section just described (even though it is better than a single coil or single condenser alone) does not give very sharp reduction of current at the cut-off frequency. Another inductance, connected in series with the load side of the circuit as shown at the right of Fig. 118 will improve the filtering action. This additional inductor has the effect of sharpening the cut-off. This circuit is called a "T" section of a filter because it resembles the capital letter T. Two of these sections may be connected as shown at (A) of Fig. 120 to give sharper cut-off. This is sometimes called a Campbell Filter

of T sections. When more than one section is used in any filter, different values of L and C are used for the center section and the end branches, as we will see. *The terminal unit of any multi-section filter is always different from the value of the units in the body of the filter.* It is evident from (A) of Fig. 120 that the joining of the two T sections gives us, at the center, a combined inductance which is equal to the sum of the two section inductances joined in series. Therefore this may be simplified as shown at (B) by considering the center inductance L_1 equal to 2 times each outside inductance, which is now called ½ L_1 for convenience. This relation should be remembered. In practical filters of this type, the center choke L_1, either consists of two chokes in series as shown at (A), each one having half the

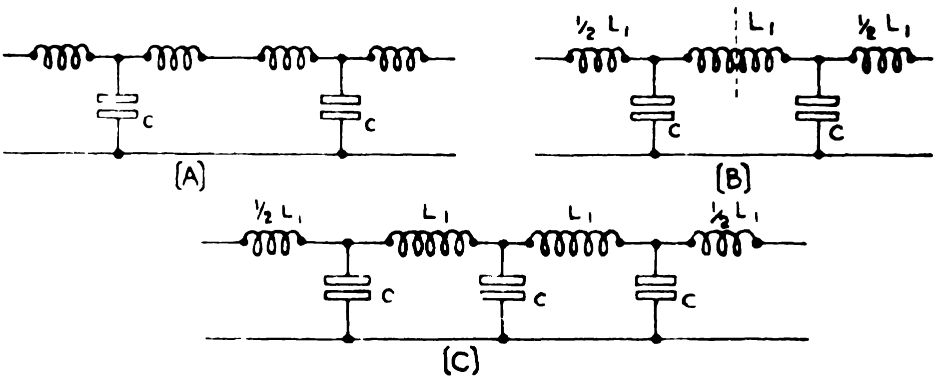


FIG 120—Method of forming a multi-section T-type filter from several single units A 2-section filter is shown at the upper right and a 3-section filter is shown at the bottom

total inductance value L_1, or if a single choke is used, its inductance must be twice as great as that of each outside or end choke as shown at (B). This is the general rule that applies to all T-section filters—the end chokes are always ½ as large as the others. A 3-section T filter would look as shown at (C).

The sharpness of the cut-offs of filters depends upon the number of sections, as well as upon the resistance of the apparatus. A filter composed of only a single section will not give as sharp a division between what is passed and what is blocked as will a filter of several sections. The number of sections which are actually used in any particular case depends, of course, upon how sharp it is desirable to have these cut-offs and upon the cost of the apparatus. In general, two or three-section filters are all that are necessary, and in some cases even one section is sufficient.

If the variation in frequency is plotted horizontally, usually upon a logarithmic scale, while the corresponding *attenuation* or "*reduction*" of the current caused by a high or low-pass filter is plotted vertically on a uniform scale, the so-called *attenuation curve* of the filter is obtained.

If the filters had no resistance or leakage losses, the T-type filter described above would give similar results to the π ("pi") type to be described next. However, under practical operating conditions it may be said that in general, the T-type of filter section is preferable to the "pi" type for *constant voltage* circuits. Of course this is only a general rule, as other factors will often alter the conditions. The calculations for the T type filter will be considered together with those of the "pi" type filter since they are identical.

182. The "pi" type low-pass filter: If the inductance is arranged with a condenser shunting the line at each end, as shown at (A) of Fig. 121 we have what is known as a π ("pi") filter section. (This name originated from the fact that the circuit diagram has the same

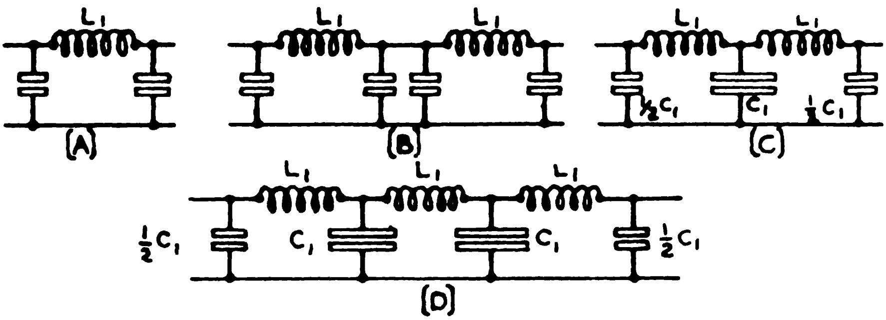


Fig. 121—(A) Single section "Pi" type filter (B) and (C) 2-section "Pi" filter (D) 3-section "Pi" type filter

form as the symbol π. The action of this type is somewhat similar to that explained for the T-section, excepting that now there are 2 condensers across the circuit. If two of these filters are connected together as shown at (B), we have at the junction a total capacitance which is equal to the sum of the two similar capacitances joined in parallel there. This circuit may be re-arranged as shown at (C) where the larger single capacitance C_1 has been put in place of the two smaller ones in parallel, and is equal to two times each outside capacitance. The outside capacitances are now called $\frac{1}{2}C_1$ for convenience. At (D) a three-section filter of the "pi" type is shown. Notice that the end capacitances are ½ the capacitances used in the repeating sections. The "pi" type filter is usually better than the T type for circuits of approximately constant current.

183. Designing T and "pi" type low-pass filters: The point at which a low-pass filter begins to cut-off is known as the *cut-off point*, and the design consists of calculating the inductances and capacitances required to locate this cut-off at the desired frequency. This frequency may be referred to simply as f. Usually the number of sections which the filter must have to make the cut-offs as sharp as desired must also be found.

For a low-pass filter of either the T or "pi" type, the values of capacitance in microfarads, and inductance in henries for a cut-off at f cycles per second, are given by:

$$L_1 = \frac{0.3183\ Z}{f} \quad \text{.....(25)} \qquad C_1 = \frac{318{,}300}{f\ Z} \quad \text{.....(26)}$$

$$\text{and } f = \frac{318.3}{\sqrt{L_1 \times C_1}} \quad \text{.....(26A)}$$

Notice that these formulas give the values of L_1 and C_1 as shown in Figs. 120 and 121. L_1 is in henries and C_1 is in microfarads. Z is in ohms

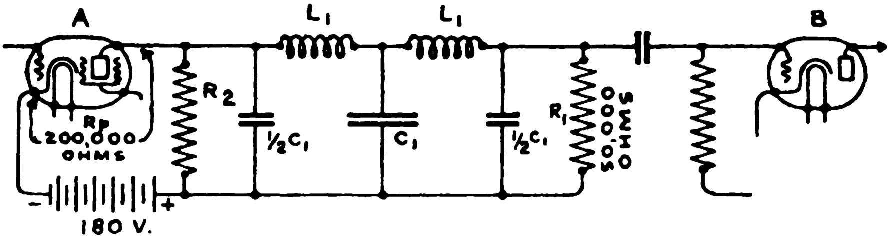


Fig 122—A practical low-pass filter used to filter high frequency (R-F) currents out of an audio amplifier

and is called the *characteristic* or *iterative impedance* of the circuit in which the filter is to be placed. The impedance Z is an important factor in the determination of the size of the condensers and coils. In practice it is desirable to terminate a filter externally both at the load and at the source of power (Fig. 122) in an impedance approximately equal to its characteristic impedance, for it is only then that the filter approaches in performance the type after which it was designed. If both the source impedance and the load impedance are known, this value is usually taken for the characteristic impedances in the above formulas. If either the load or the source impedance is known, this is taken as the characteristic impedance in the formulas, and then an impedance is connected at the other end so as to make it of the same combined impedance value, as will be illustrated in the example to follow.

If a certain ready-built fixed filter is to be employed, and it is desired to know what impedance to terminate it in, it may be found from the expression for the "characteristic" impedance *at zero frequency* which is,

$$Z_0 = \sqrt{\frac{L_1}{C_1}} \qquad \text{where: } Z_0 = \textit{ohms},\ L_1 = \textit{henries},\ C_1 = \textit{farads}$$

This is independent of the number of sections and, depends only on the inductance and capacitance used. There is always one best load impedance for a particular filter. The best load is a pure resistance, and

loads having reactance or resonant characteristics will upset the filter characteristics very much.

Example: The low-pass filter shown in Fig. 122 is to be connected between two amplifying tubes as shown. Radio and audio frequencies are fed into the amplifier and it is desired to separate them and amplify only the audio frequencies. Assume 20,000 cycles (the limit of audibility) as the cut-off point. The internal plate circuit resistance of tube A is 200,000 ohms. Plate coupling resistor R_t into which the filter terminates is 50,000 ohms. Design the filter if it is of the type shown.

Solution: Since the terminating impedance R_t is 50,000 ohms, the input impedance to the filter should also be made equal to this value by connecting resistor R_2 in parallel with the plate resistance R_p of the tube. Then since:

$$\frac{1}{R_{total}}=\frac{1}{R_2}+\frac{1}{R_p} \text{ we have } \frac{1}{50{,}000}=\frac{1}{R_2}+\frac{1}{200{,}000}$$

from which $R_2=66{,}666$ ohms.

The filter therefore should be designed for 50,000 ohms, since it will terminate with this same impedance at both ends,

$$\text{We now have: } L_1=\frac{0.3183\ Z}{f}=\frac{0.3183 \times 50{,}000}{20{,}000}=0.8 \text{ henries.}$$

ans.

$$\text{and } C_1=\frac{318{,}300}{f\ Z}=\frac{318{,}300}{20{,}000 \times 50{,}000}=0.00032 \text{ microfarads.}$$

(approx)

The capacitance of the first and last condensers must each be equal to ½ C_1, or .00032÷2, or .00016 microfarads. It is not practical to obtain the exact values of L_1 and C_2 as computed above. In practice, values of commercially available coils and condensers as close as possible to these values should be used and the filter re-computed to see how much f and Z have changed.

In filter construction, the resistance should be kept as low as practicable since the effect of resistance is to introduce some attenuation in the passed band, and to round out the abrupt changes at cut-off.

If the inductors have iron cores and carry much current, they should be provided with an air gap so that their values will not change appreciably with changing current. They may also need to be magnetically shielded from one another, as any coupling between them may change the characteristics of the filter. In radio-frequency circuits, the choke coils should be of low-loss type.

It will be seen from an examination of (B) of Fig. 120, and (C) of Fig. 121, that a two section T filter is quite similar to a two section "pi" filter at the center. Whether to use end sections of the "pi" or T type in any case, depends on the problem in hand and the rules already given are good ones to follow. The "pi" section type of filter ends with a condenser and in some applications advantage may be taken of this fact to use this same condenser to by-pass any radio-frequency currents present. The sum total of capacitance and inductance used in both types is the same, for an equal number of sections. Of course, since every filter has some resistance, the filter always causes some reduction in the strength of

the currents passed. Also the current suppressed by the filter is never reduced entirely to zero at any frequency, although the zero value may be approached by using a number of well designed sections.

184. Some applications of low-pass filters: A practical application of the low-pass filter is in the "B" power supply unit in electric radio receivers. In this case, the pulsating "rectified" direct current is passed through the choke coils with some opposition but, since direct current cannot pass through a condenser, the direct current is kept in the correct path. The choke coils tend to oppose any pulsations in the current. The high-capacity condensers in the filter absorb the pulsations in this direct current. This leaves the output current free of all pulsations which would otherwise cause "hum" in the receiver.

In most "B" power units a two-section filter is employed, comprising

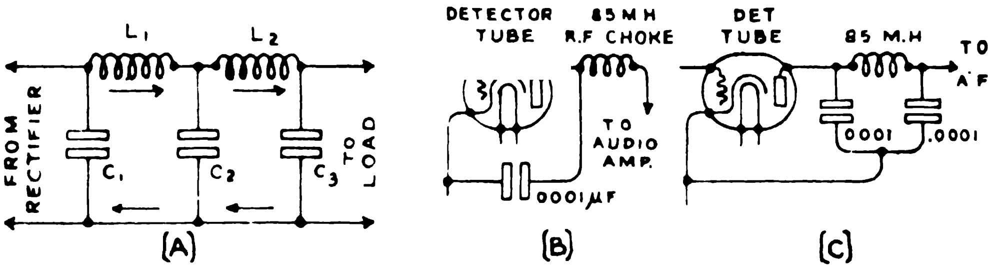
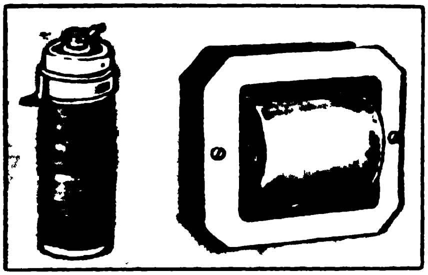


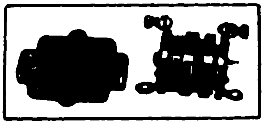
Fig 123—(A) A type of low-pass filter section commonly used in B-power units of A-C electric radio receivers (B) Low pass filter section following the detector tube in a radio receiver to keep the r-f currents out of the audio amplifier, but pass the lower frequency audio currents through (C) Improved form of the filter at (B).

two choke coils and two or three filter condensers, as shown in (A) of Fig. 123 Assuming that 30-henry chokes and 2-microfarad condensers are used, a filter of this type will pass all currents having a frequency of less than about 20 cycles, including direct current. This filter will block all currents which have frequencies above 20 cycles, however, which includes the 60-cycle hum-current which we wish to eliminate, and also practically all of the "line" noises which are present. Such a filter is ideal for the purpose for which we wish to use it. A 30-henry filter-choke and an electrolytic condenser-unit used in a filter of this kind, are shown at the left of Fig. 124. At (B) of Fig. 123 is shown the simple low-pass filter arrangement commonly used in the plate circuit of the detector tube in a radio receiver. The r-f choke coil is an air-core coil of about 85 millihenries inductance, designed to offer low impedance to the passage of audio-frequency currents from 0 to about 10,000 cycles through it. It does, however, present a high impedance to the flow of radio-frequency currents (about 20,000 cycles—up). The by-pass condenser, usually of from .0001 to .0005 mf. capacitance, acts as a by-pass for all radio-frequency currents which exist in the plate circuit of the detector tube.

At (C) is shown an improved form of detector plate filter which is now being used in many receivers. It has two condensers instead of one. This form a "pi" section filter which is more effective for this purpose than that shown at (B), since the condenser on the right also helps to by-pass the radio-frequency currents. An 85 millihenry r-f choke coil and 0001 mf. by-pass condenser actually used for this purpose are shown at the right of Fig. 124.

Low-pass filters are also used as tone controls for suppressing the high frequency audio currents in audio amplifiers, and in interference eliminators for suppressing extraneous electrical disturbances. In some electro-dynamic loudspeakers, high-pass filters are used to suppress any 60 cycle hum which may be present, but they pass through all audio frequencies above this. These will be considered in detail later at appropriate places.





Courtesy Aerovox Wireless Corp and Pilot Radio & Tube Corp

Fig 124—Left An electrolytic condenser and a 30 henry choke used in the low-pass filter of a B-power supply unit
Right 0001 mf condenser and 85 mh choke used in the low-pass filter following a detector tube

185. High-pass filters: A simple type of high-pass filter is shown in (A) of Fig. 126. The high-frequency current passing through the circuit encounters very little impedance from the series condenser, but encounters a high impedance in the inductance, so not much is shunted. The low-frequency currents attempting to pass through however, encounter high impedance in the condenser and are easily short-circuited out by the inductance—none of them, therefore, getting through. The action of this type of filter is shown at (B). Notice that the low frequencies are cut off and the high frequencies are passed through. At (C) is shown a single section T-type high-pass filter.

At (A) of Fig. 127 we have two single section T-type filters joined to make a 2-section unit. The part of the circuit between the two chokes has two similar condensers in series. They may be replaced by a single condenser C_1 having half the capacitance of either one. To keep our condenser notations in accordance with those used in discussing low-pass filters, the equivalent inside condenser is called C_1. Each outside condenser then has a value of 2 C_1 as shown at (B). Therefore in T type high-pass filters, the end capacitances are *each twice* the capacitance

used in the repeating sections, since the latter is the sum of two section-capacitances in series.

At (C) is shown a "pi" type single section high-pass filter. When two or more such sections are joined together as at (D), we have two similar inductances in parallel with each other at the center. These may be considered as being replaced by a single inductor L_1 having half the inductance of either one. Therefore the outside inductors are each equal to $2L_1$. Thus in a multi-section "pi" type high-pass filter, each end inductance is twice the inductance used in the repeating sections, since the latter is the sum of two section-inductances in parallel. Here again, the larger the number of sections, the more perfect is the cut-off.

186. Designing high-pass filters: For a high-pass filter of either the T or "pi" type, the values of capacitance in microfarads, and inductance

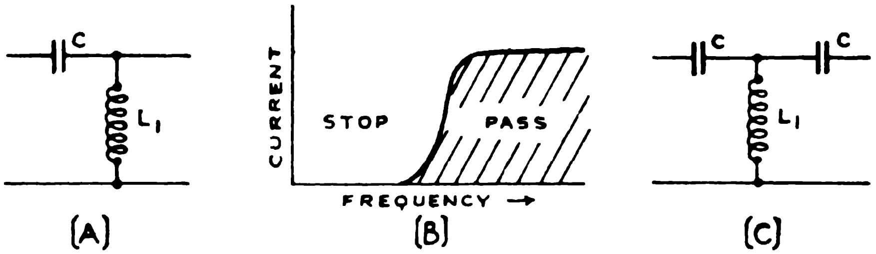


Fig. 126—(A) A single section high-pass filter (B) Transmission characteristic of a high-pass filter (C) Single section T-type high-pass filter

in henries for a cut-off at f cycles per second are given by:

$$L_1 = \frac{0.07958\ Z}{f} \quad \text{.........}(27) \qquad C_1 = \frac{79{,}580}{f\ Z} \quad \text{.........}(28)$$

$$\text{and } f = \frac{795.8}{\sqrt{L_1 \times C_1}} \quad \text{.........}(28A)$$

These formulas give the value of L_1 and C_1 as shown in (B) of Fig. 127. Z is in ohms, and applies exactly in the same way as in the formula for low-pass filters in Article 183. The same precautions regarding source and terminal impedances must be observed. The following example will serve to illustrate the use of the formulas.

Example: The high-pass filter shown in Fig. 128 is to be connected between two vacuum tubes in an r-f amplifier, as shown. Radio and audio frequencies are fed into the amplifier and it is desired to separate them and amplify only the radio frequencies. Assume 20,000 cycles, the upper limit of audio frequencies, as the cut-off point. The internal plate circuit resistance R_p of tube A is 200,000 ohms. The 50,000 ohm plate coupling resistor R_c is in parallel with this at the source of the filter. Assume the input impedance of tube B to be infinitely great.

Solution: Since R_p and R_c are in parallel, their joint resistance R is:

$$\frac{1}{R}=\frac{1}{R_p}+\frac{1}{R_c}=\frac{1}{200{,}000}+\frac{1}{50{,}000}=40{,}000 \text{ ohms.}$$

This is the effective input impedance of the source. The filter therefore should be designed for 40,000 ohms, and the other end should be terminated with resistance R_t of approximately the same value.

From the formulas for high-pass filters we obtain.

$$L_1=\frac{0.07958\ Z}{f}=\frac{0.07958 \times 40{,}000}{20{,}000}=0.16 \text{ henries (approx.)}$$ ans.

$$C_1=\frac{79{,}580}{f\ Z}=\frac{79{,}580}{20{,}000 \times 40{,}000}=0.0001 \text{ microfarads (approx.)}$$ ans.

The filter is made up of two "T" sections and therefore the capacitances of the two outside condensers must each be equal to 2 x 0.0001, or 0.0002 microfarads.

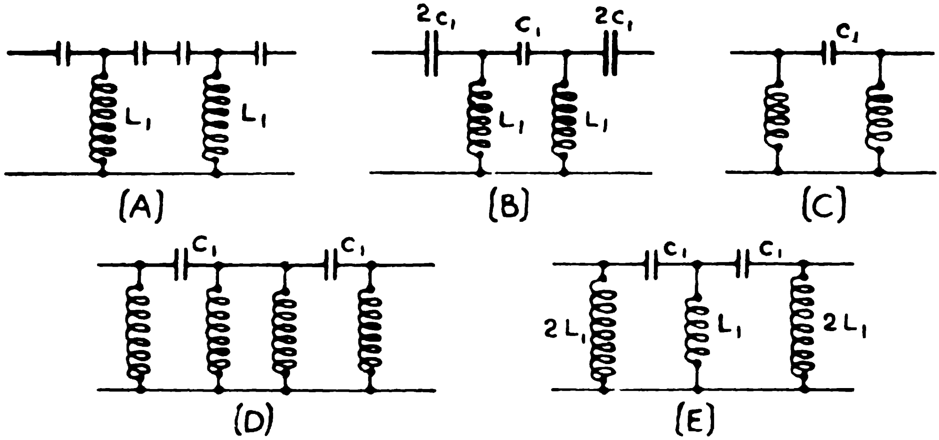


Fig 127—Various arrangements of T and "Pi" section high-pass filters (A) and (B) 2-section T-filters. (C) single section "Pi" filter. (D) and (E) 2-section "Pi" filters

High-pass filters are sometimes used in the audio amplifiers and electro-dynamic loud speakers of radio receivers, to suppress 60 or 120 cycle hum currents, and pass the currents of all higher frequencies.

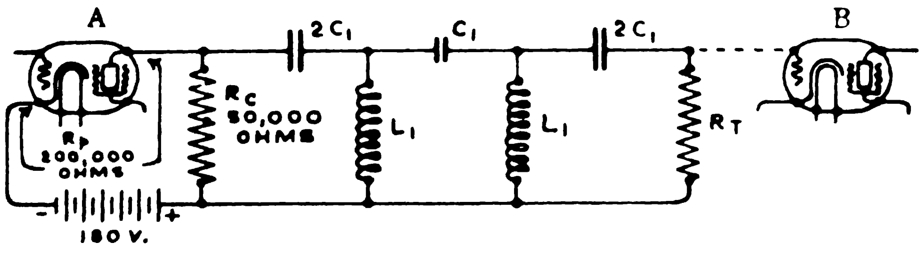


Fig 128—A practical high-pass filter for keeping low frequency (A-F) current out of a high frequency (R-F) amplifier

187. Band-pass filters: If a low-pass filter of say 1000 cycle cut-off were connected to a high-pass filter of say 500 cycle cut-off and

then to the load, as shown at (A) of Fig. 129, it is evident that below 500 cycles nothing could get through due to the high-pass filter, and above 1,000 cycles nothing could get through due to the low-pass filter. Therefore the frequencies transmitted would be limited to those lying between 500 and 1,000 cycles as shown at (B). This combination is known as a *band-pass* filter, because it passes only a narrow band of some pre-determined frequencies. The circuit at (A) is made up of two "pi" section filters. It is not necessary to make separate filters since the various parts can be

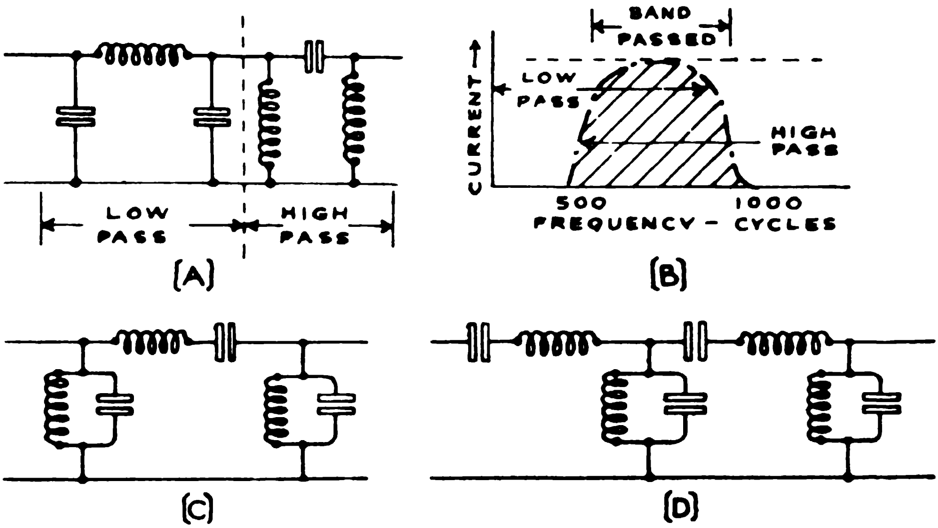


Fig 129—(A) Combination of single "Pi" low-pass and high-pass filters to give the band-pass effect shown at (B). A practical combined band-pass "Pi" filter is shown at (C) A T-type band-pass filter is shown at (D)

combined into a single filter section as shown at (C), and the same results obtained. This may also be made with two T-section filters in the same way as shown at (D). The type shown at (D) will pass two separate bands of frequencies. This makes it objectionable for use in many applications where only a single band is to be passed. Usually it is necessary and desirable to pass only one band of frequencies rather than two, and since it also takes less apparatus, the filter circuits of Fig. 130 are the ones which are most generally encountered in ordinary band-pass filter work. A little study will show that each of the filter circuits shown here is really nothing more than the general circuit shown in (D) of Fig. 129, but with one or more of the inductances or condensers left out.

A study of (D) shows that the series resonant circuits allow one particular frequency to flow through them more easily than any other. The parallel resonant circuits across the line impede one frequency only, and allow all others to flow right through them, thus by-passing them

across. The circuits are so designed that the one frequency which gets through the series resonant circuits is the only one not short-circuited by the parallel resonant circuits.

Every tuned circuit in the ordinary tuned radio-frequency radio receiver is really a one-section filter, but in this case it is a band-pass filter designed to pass currents of one particular small band of frequencies around that to which it is tuned, and block all others. Intermediate fre-

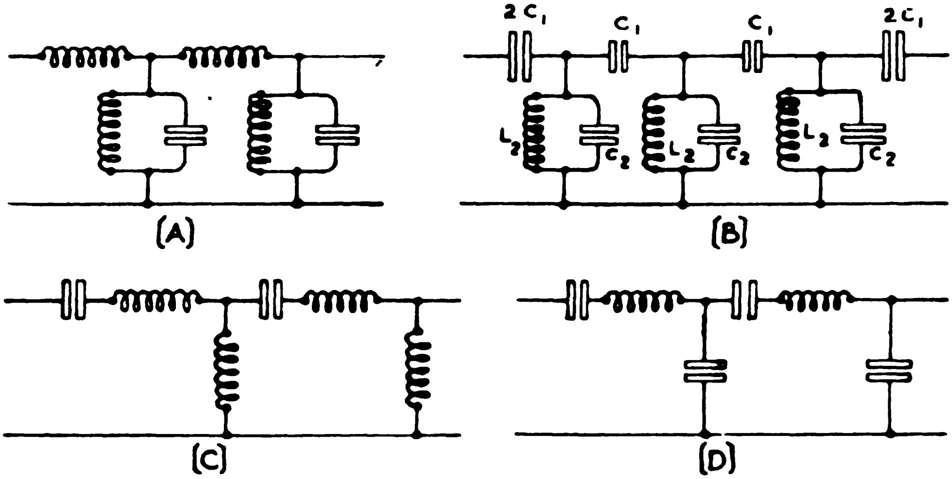


Fig 130—Four commonly used band-pass filter circuits

quency transformers in superheterodyne receivers are designed for the same purpose, and in carrier telephone work, filters of all three types are widely used. Various special forms of band filters and band selectors will be studied later in Arts. 360 and 391, in connection with radio receivers.

188. Design of band-pass filters: In designing a band-pass filter three quantities are usually known. These are: the impedance (Z) the filter is to work out of (or into), and the upper and lower cut-off frequencies (f_2 and f_1 respectively). With this data as a basis, the capacitances and inductances required for the filter may be calculated by formulae:

$$C_1 = \frac{f_2 - f_1}{4\pi f_1 f_2 Z} \ (\textit{farads}) \qquad (29)$$

$$C_2 = \frac{1}{\pi (f_2 - f_1) Z} \ (\textit{farads}) \qquad (30)$$

$$L_2 = \frac{f_2 - f_1) Z}{4\pi f_1 f_2} \ (\textit{henries}) \qquad (31)$$

C_1 and C_2 are the capacitances in farads, as indicated in the conventional band-pass filter shown in Fig. 130, L_2 is the inductance of each coil in *henries*, f_2 is the higher cut-off frequency in cycles per second and f_1 is the lower cut-off frequency, Z is the characteristic impedance of the filter. As with the other filters described, Z should be made as nearly equal to the impedance of the source and load, as practical. In practice, the impedance selected is usually that of the line, for some frequency near the middle of the pass-band. The use of these formulas may be illustrated by the following example:

Example: It is desired to make a band-pass filter for a superheterodyne receiver; the filter is to pass a band 10 kc wide and is to have its cut-off frequencies at 100 and 110 kc. It is to be terminated at one end by a resistor of 50,000 ohms which is in the plate circuit of a 227 type vacuum tube having a plate impedance of 10,000 ohms; at the other end it is terminated by a variable grid leak which is adjusted to match the impedance of the filter.

Solution: Impedance R, of the parallel circuit feeding into the filter:

$$\frac{1}{R}=\frac{1}{50{,}000}+\frac{1}{10{,}000} \text{ or } R = 8{,}350 \text{ ohms. (approx.)}$$

$$C_1=\frac{f_2-f_1}{4\pi f_1 f_2 Z}=\frac{110{,}000-100{,}000}{4\pi\times 100{,}000\times 110{,}000\times 8{,}350}=.0000087 \text{ microfarads.}$$

$$C_2=\frac{1}{\pi(f_2-f_1)Z}=\frac{1}{3.14\times 10{,}000\times 8{,}350}=.0039 \text{ microfarads.}$$

$$L_2=\frac{(f_2-f_1)Z}{4\pi f_1 f_2}=\frac{10{,}000\times 8{,}350}{4\pi\times 100{,}000\times 110{,}000}=.0006 \text{ henries.}$$

Note: In the above solutions C_1 and C_2 have been converted to microfarads by multiplying the answers given by the formulas by the conversion factor 1,000,000.

189. The band-suppression filter: By inverting the band-pass filter, the filters shown at (A) and (B) of Fig. 131 are obtained. This is called a *band-suppression filter*. The characteristic of this type is shown at (C). Filters of this type are commonly used to suppress electrical disturbances lying within some particular band of frequencies.

The "*wavetrap*" sometimes used in the antenna circuits of radio receivers is a form of band-suppression filter. As shown at (A) of Fig. 132, a series wavetrap consisting of a coil and a variable condenser connected in parallel with each other, are connected in series with the antenna circuit of a radio receiver. When the filter is tuned to resonance for a given frequency, signals of that frequency cannot enter the receiving set since the parallel resonance filter circuit presents a very high impedance to the flow of current of the frequency to which it is tuned. It can be designed to suppress a band of frequencies about 10 kc wide, depending upon the width of its resonance curve. It is a "rejector" wavetrap.

If the filter is shunted across the antenna and ground connections as shown at (B), the signals to which the filter is tuned will go through the receiver while the other signals will be shunted across through the

filter since it offers a very high impedance to signals of its resonant frequency and a low impedance to all others. A band of frequencies about 10 kc wide (depending on the resonance curve of the filter) will pass through the receiver coil for any setting of the filter condenser. This is an *acceptor wave trap.* The filter tunes more sharply if it is inductively coupled to the antenna circuit by winding a 5-turn coil over the coil of the filter and connecting it in series with the coil in the antenna circuit.

190. General uses of filters: Electrical filters are used extensively in studying the characteristics of communication equipment and in the transmission of electrical impulses of multiple frequency as exemplified by speech or music Such filters consist of capacitance and inductance networks so designed that they allow certain frequencies to

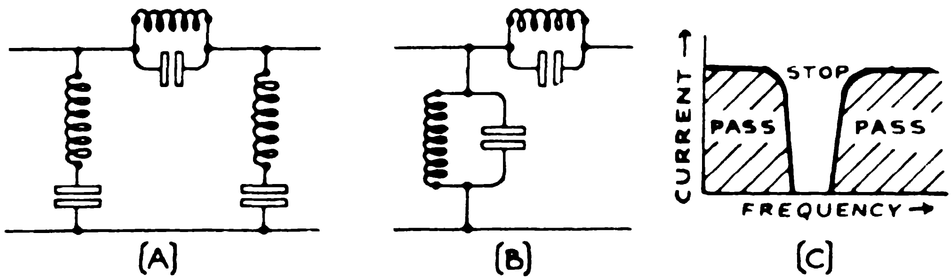


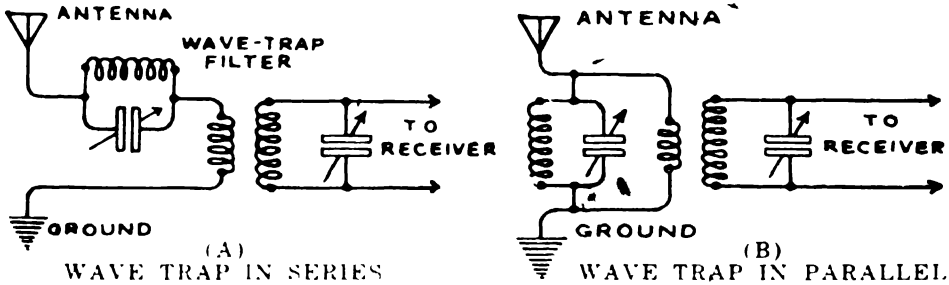
Fig 131—Two forms of band-suppression filters and the transmission characteristic produced

pass readily through them while at the same time they attenuate other frequencies strongly. By the use of filters for instance, a composite sound may be divided into several parts, or a fault in telephone apparatus may be remedied by attenuating or placing emphasis on certain ranges of the frequency spectrum.

By means of band filters, it becomes possible to separate in accordance with the frequency. We are thus enabled to transmit a number of messages simultaneously over the same telephone circuit, or through the air, and to separate these messages at the receiving station. For example, in the multiplex telegraph system, known as the carrier current system, there are transmitted over the same pair of wires simultaneously, 10 telegraph messages which are carried by currents of ten different frequencies, all somewhat above those of the voice range; two ordinary telegraph messages, carried by direct currents, i.e., zero frequency currents; and an ordinary telephone conversation This multiplex telegraph system is in operation between many of the important cities of the country. In every case, the separation of the different messages is accomplished by means of electrical filters which select a single band of frequencies for transmission to the apparatus to which they are connected and fail completely to transmit all the other messages which may be simultaneously received.

Filters are being used more and more in radio receivers in order to obtain certain desired characteristics which are either otherwise unobtainable, or else would be very much more expensive if arrived at by other methods. We will examine these in detail at the proper points during our study of radio receivers.

Resistance-capacity type filters consisting merely of a resistor in series with one side of the line, and one or more condensers across the line, are used extensively in audio amplifiers as we shall see presently. They have one great advantage in this type of work in that they are cheap and do not have any bothersome resonant frequency points which might be objectionable if the ordinary inductance-capacity filters were used.



(A)
WAVE TRAP IN SERIES
(REJECTOR CIRCUIT)

(B)
WAVE TRAP IN PARALLEL
(ACCEPTOR CIRCUIT)

Fig. 132—Band-suppression wave traps or filters connected to the antenna circuit of a radio receiver to eliminate interference from unwanted stations. (A) series wave trap. (B) Shunt or parallel wave trap.

Band-pass filters are being used extensively in radio receivers of both the tuned-radio-frequency (T.R.F.) and the superheterodyne type. They are arranged to pass a band of frequencies approximately 10 kilocycles wide.

In the T.R.F. receivers the 10 k.c. frequency band passed through, can be shifted throughout the entire broadcast band frequency range from 500 to 1500 k.c. by means of the tuning condensers. In the superheterodyne circuit the frequency band-passed is set fixed at some definite value in the intermediate amplifier. At the present time most supers are designed to pass through their intermediate amplifier stages, a 10 k.c.-wide band of frequencies at about 175 or 180 kilocycles. That is, if the intermediate amplifier is designed for, say 175 k.c., then the band-pass filter is arranged to pass the band from 170 to 180 k.c. and sharply cut off all frequencies above and below this value. The simple form of band-pass filter usually employed in circuits of this kind is a bit different from the usual form. In the plate circuit of one amplifier tube we have the primary of an intermediate transformer, forming with its tuning condenser a *parallel* resonant circuit which places a high impedance in the plate circuit of the tube at the particular frequency (or 10 k.c. band of frequencies) to which it is tuned to resonance. This causes maximum amplification of the signals at this band of frequencies. The secondary of the coupling transformer forms a *series* tuned circuit (at the same frequency band) with its tuning condenser, and hence this tends to allow currents of this particular frequency (or band of frequencies) to be passed and to circulate freely and set up comparatively large voltages across the grid input circuit of the following amplifier tube. The net effect then is simply to pass through the band of frequencies to which the primary and secondary tuned circuits of the coupling transformer are resonant, and reduce or completely stop the flow of currents of all other frequencies. The system will be studied in more detail later in

connection with superheterodyne receivers. The tuned circuits are made broad enough so they pass a band of frequencies about 10 kc wide, instead of passing only a single frequency as a sharply tuned resonant circuit would do.

REVIEW QUESTIONS

1. Give three examples of mechanical filtering devices and explain their action.
2. What do you understand the term "electrical filter" to mean?
3. What is a low-pass filter? Draw a circuit diagram of (a) a single section T filter of this type (b) a "pi" section.
4. Describe one application of a low-pass filter.
5. What is a high-pass filter? Draw a circuit diagram of (a) a single section T filter of this type. (b) a "pi" section
6. Describe one application of a high-pass filter.
7. What is a band-pass filter? Draw a circuit diagram of a 2 section filter of this type
8. Give an application of a band-pass filter
9. What is a band-rejector filter? Draw a circuit diagram of a 2-section filter of this type.
10. What three principles of alternating currents do the operation of electrical filters depend upon?
11. What is the effect of building a filter with several similar sections rather than a single section?
12. What is meant by the cut-off point of a filter? Draw curves illustrating the point of cut-off for each of the four types of filters.
13. A 2-section low-pass filter connected between the output tube and the loud speaker of a radio receiver is to cut-off at 4000 cycles. The plate impedance of the tube circuit at its source is 2000 ohms. What must be the values of the inductance and capacitance used in the filter? Draw the circuit diagram with all constants marked (a) if the filter is of the "pi" type (b) if it is of the T type
14. A 2-section high-pass filter connected between the output tube and the loudspeaker of the above radio receiver is to cut off at 100 cycles. What must be the values of the inductance and capacitance used. Draw the circuit diagram with all constants marked, (a) for a "pi" type filter, (b) for a T type filter.
15. What is the effect of resistance in the elements of a filter?
16. It is desired to design a band-pass filter to pass a 10 kc band of frequencies from 170 kc to 180 kc in a 175 kc intermediate amplifier of a superheterodyne receiver. The source and load impedances may be taken as 200,000 ohms. The filter is to be arranged as shown at (B) of Fig. 130. Calculate the values of the circuit constants required.

CHAPTER 13

ELECTRICAL MEASURING INSTRUMENTS

EXTERNAL EFFECTS OF CURRENT FLOW — MAGNETIC TYPE INSTRUMENTS — TANGENT GALVANOMETER — D'ARSONVAL GALVANOMETER — BALLISTIC GALVANOMETER — THE WESTON MOVEMENT — D. C. AMMETER AND SHUNTS — USE OF AMMETERS — EXTENDING RANGE OF D. C. AMMETERS AND MILLIAMMETERS — HOT WIRE AMMETERS — THERMOCOUPLE INSTRUMENTS — DIRECT CURRENT VOLTMETER — INCREASING D. C. VOLTMETER RANGE — MAKING D. C. VOLTMETER FROM MILLIAMMETER — HIGH RESISTANCE VOLTMETER — COMBINED VOLTMETERS AND AMMETERS — WATT METERS — A. C. METERS. — RECORDING WATT-HOUR METER — POWER CONSUMPTION TEST OF RADIO RECEIVER—INCLINED COIL, MOVABLE IRON, AND ELECTRO-DYNAMOMETER TYPE A. C. METERS — DRY PLATE RECTIFIERS AND COPPER-OXIDE TYPE METERS — RESISTANCE MEASUREMENT BY AMMETER & VOLTMETER, VOLTMETER ALONE, OHMMETER — WHEATSTONE BRIDGES FOR MEASURING RESISTANCE, INDUCTANCE OR CAPACITANCE — THE WAVEMETER — MEASURING FREQUENCY AND WAVELENGTH — REVIEW QUESTIONS.

191. External effects of current flow: It must be evident to the student at this time that the two quantities which we deal with most in electrical work are the *current* or rate of flow of electrons through the circuit, and the *voltage* or electrical force which causes the drift of electrons. The *electrical power* in watts may also be considered. It is necessary for us to be able to accurately measure these quantities, in order to design, build and test electrical and radio equipment. Since we cannot see, taste, smell, hear or feel an electric current flowing through a circuit, we must employ one or more of its effects which we can observe, for its measurement.

First, current flowing through a circuit, always produces around it an associated magnetic force or field whose strength is proportional to the rate of current or electron flow (amperes) through it. This is known as the *magnetic effect*, and is illustrated at (A) of Fig. 133. Second, a current flowing against the resistance of a circuit always produces heat, proportional to the square of the current. This is the *heating effect*, as shown at (B). Third, if current is sent through an acid or salt solution between two conducting plates, electrolytic action will take place, the solution will be dissociated chemically and metal will be plated out on one of the plates. This is known as the *electro-chemical effect* and is illustrated at (C).

Theoretically, any of the three effects mentioned and described above could be employed for the measurement of electric current and e. m. f. simply by measuring the intensity of the effect produced by the passage of the current to be measured. Practically however, the magnetic effect is employed most frequently, in what are known as the *magnetic type* electrical measuring instruments, and the heating effect is used in the

hot wire instruments used for special applications. The electro-chemical effect is not used for current measurement in practical work.

192. Magnetic type instruments: Instruments which depend for their operation on the electromagnetic effect of the electric current are called *galvanometers*, and are the most common types for both d-c and a-c measurement work on account of their ruggedness, high degree of accuracy, simplicity and portability. Since the magnetic field existing around an alternating current carrying wire varies in strength and direction with the current, a-c ammeters and voltmeters are constructed differently than d-c meters. They will be studied later. We will first study the simple forms of galvanometers which led up to the development of the Weston movement which forms the basis of most high grade magnetic type ammeters and voltmeters in use today. Although these galvanometers are not used to any extent at present, a study of them will help the student to easily understand the operation and construction of our present forms of instruments.

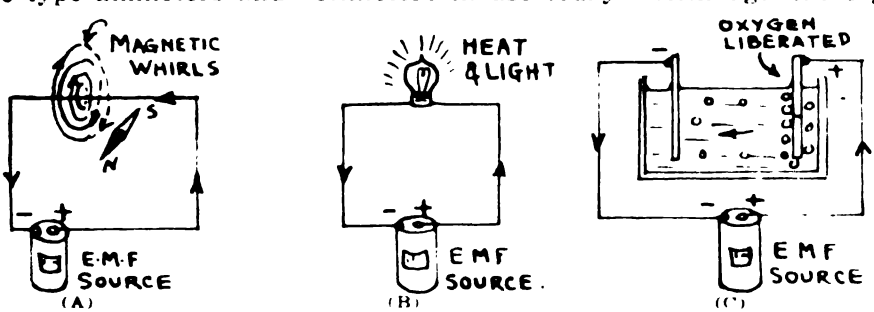


Fig 133—Magnetic, heating and electrochemical effects of an electric current

193. Tangent galvanometer: Probably the simplest type of magnetic current indicating and measuring instrument, is the tangent galvanometer shown at (A) of Fig. 134. A description of the construction and action of this old form of instrument follows:

The tangent galvanometer consists of a vertical coil of insulated copper wire, with a small permanent-magnet compass needle mounted in a horizontal plane at its center, as shown in (A) of Fig. 134. Since this compass needle is free to rotate in a horizontal plane, it will point exactly *north* and *south* in the earth's magnetic field when no current is flowing through the coil. To use the galvanometer, the coil (with no current flowing) is first turned around so its plane lies directly in line with the compass needle, i.e., pointing in a north and south direction. When this is done, the compass needle will be directly over the "zero" mark on the scale mounted underneath it

Now the current to be measured is sent through the coil of wire This produces, inside of the coil, a magnetic field whose strength depends upon the number of turns of wire and the current. With the current direction shown at (A) of Fig 134, a N pole is produced at the front face of the coil and a S pole is produced at the rear, as marked. The S pole of the coil attracts the N pole of the compass needle and makes it tend to move around in a clockwise direction, against the force of attraction of the earth's magnetic field for it. The N pole of the coil will also tend to attract the S pole of the compass needle around in the same direction. The result is that the passage through the coil, of the current to be measured, produces a deflection of the needle around from its "zero position", the tangent of the angle of deflection thus produced being proportional to the strength of the current flowing through the coil. For this reason it is called a "tangent galvanometer". If the galvanometer has been prev-

iously calibrated, and the current values are already marked on the scale below the compass needle, the current in amperes flowing when a given angle of deflection is produced can be read directly from the scale. In this way, the instrument can be used as an ammeter, to measure current.

We have here, a device for measuring the flow of electric current by means of the magnetic force of attraction it produces on a movable magnet at the center. This is called a *galvanometer*.

This form of galvanometer has several disadvantages, the most important of which are as follows: (1) it is not readily portable and compact; (2) the readings are affected by any external magnetic fields which may exist around near the instrument; (3) it is not sensitive to small currents since the magnetic field produced by the current must pass through a long air path; (4) the instrument can only be used when the plane of the coil is lined up so it points N and S, and the instrument must be leveled up to permit free rotation of the compass needle every time it is used; (5) it also has the disadvantage that in its simplest form it does not return to the zero point very quickly when the current flow through the coil is stopped, and also, the needle oscillates back and forth for quite a long period of time before it finally comes to rest at any position; (6) the accuracy of its readings are also affected by changes in the earth's magnetism, which as we know may be severe during magnetic storms and times of "sun-spots".

194. D'Arsonval galvanometer: The foregoing objectionable features of the original form of tangent galvanometer, led to its improvement by several men, but perhaps the most important improved form was that of D'Arsonval. This is called the D'Arsonval galvanometer, after its inventor, and is shown in simple form at (B) of Fig. 134. Its construction and operation is as follows:

A permanent horseshoe magnet is placed with its poles as shown and a movable rectangular coil of very fine insulated wire is suspended between the poles at the top by a fine phosphor bronze or steel wire which also serves as one current lead from the coil. The other connection is in the form of a very flexible spiral of soft copper ribbon connected to the bottom of the coil, but exerting no appreciable restraint to its rotation. When the current to be measured flows through the coil, a magnetic field is produced in and around it, the poles being at the back and front faces of the coil as usual. The attraction between the S pole of the coil and the N pole of the permanent magnet, and that between the N pole of the coil and the S pole of the permanent magnet causes the coil to turn around in a clockwise direction (looking down on the top), the amount of deflection being approximately proportional to the current flowing through the coil. The coil will of course move clockwise or counter-clockwise depending on the direction of the current through it. The tendency to rotate is opposed by the twisting or torsion of the suspension wire, and the motion continues until the turning effort (or torque) due to the current is equal to the opposing torque of the suspension wire. A stationary cylindrical soft iron core is placed inside of, and clearing the coil, and is supported from the back. Its purpose is to strengthen the magnetic field between the poles of the permanent magnet, by reducing the reluctance of the flux-path, and hence it makes the instrument more sensitive; that is, a given current sent through the instrument will produce a larger deflection of the coil.

It must be remembered that the coil rotates freely in the small annular space between the magnet poles and the soft iron core. If the coil is wound on a thin non-magnetic metallic frame such as aluminum, the instrument is very *"dead beat"*, for the instant the coil moves, eddy currents are induced in the frame in such a direction as to tend to stop its movement. This damps the motion of the coil so it quickly

comes to rest when the current flow through the coil is stopped or when it is deflected to any position, instead of oscillating back and forth for several seconds.

A mirror is usually attached to the coil so that a beam of light from an incandescent lamp, directed on it by a system of lenses, will be reflected back on to a semicircular graduated scale placed about one meter from the mirror. When the coil deflects, the mirror deflects with it and the light is reflected back to the scale at an angle as shown at (C). Thus a very small deflection of the coil and mirror will produce a very much enlarged or amplified deflection of the beam of light on the scale so that it can be read accurately by means of a telescope. A complete D'Arsonval galvanometer of this type is shown at the right of Fig. 135. The small lamp which produces the beam of light, and the telescope and scale are supported at the left by an arm. The galvanometer movement and mirror are enclosed in an iron case which shields it from external magnetic fields and is arranged to be mounted on a wall in the position shown. Since the coil and suspensions are exceedingly light, and there are many turns of fine wire on the coil, galvanometers of this type can be made sensitive enough to give a deflection (of the spot of light) of one millimeter on a scale one meter distant from the mirror, for a current of .000000001 amperes. If a resistance of 1,000 megohms is connected in series with the moving coil, an e. m. f. of one volt applied to the meter will produce a deflection of one millimeter division. Therefore it can also be used as a voltmeter by connecting a high resistance in series with it.

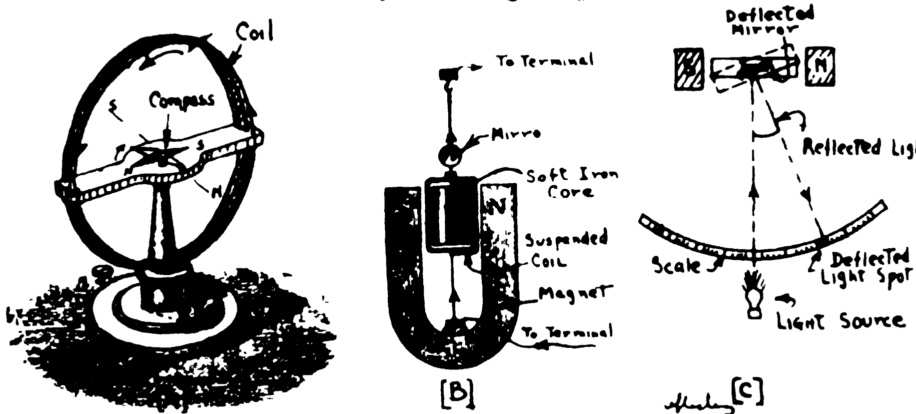


Fig 134—(A) Simple form of tangent galvanometer (B) D'arsonval galvanometer movement (C) Light beam arrangement for amplifying movements of the mirror

The D'Arsonval galvanometer is quite an improvement over the old tangent galvanometer in that it is not affected by changes in the earth's magnetic field or by external magnetic fields and can therefore be used in close proximity to electrical apparatus. It can also be built very sensitive, but it has several limitations which make it suitable only for use in laboratory work where it is permanently mounted, usually on a wall. It is too large, bulky, and delicate to be conveniently portable, also it must be carefully leveled up so the coil moves freely without touching the pole pieces. This is accomplished by the leveling screws and tension screws provided.

Notice that in the D'Arsonval instrument the permanent magnet is stationary and the coil moves. This construction in refined form is used in most direct-current electrical measuring instruments today.

195. Ballistic galvanometer: A form of D'Arsonval galvanometer which is used for measuring momentary currents (such as currents during discharge of condensers, currents produced by momentary electromagnetic induction etc.) is called a *ballistic galvanometer*.

It is constructed with a wide coil designed to have considerable mass and is arranged so it has very little damping effect. If a momentary current is passed through its coils, the impulse given to the movable coil does not cause appreciable movement at once, owing to the inertia of the heavy moving parts, the result being a slow "swing" of the system. The maximum deflection or "throw" must be noted carefully on the scale, just at the point where the coil and spot of light begin to swing back to zero. The throw is a measure of the *quantity* of electricity sent through the coil. The instrument looks like that shown at the right of Fig. 135. It has a resistance of about 2000 ohms and will produce a deflection of 1 mm. on the scale by a quantity of electricity of about .003 micro-coulomb, the time of the ballistic throw from the position of rest to that of maximum deflection being about 5 seconds.

Ballistic galvanometers are used in many condenser measurements, where the current discharges from the condenser too rapidly to operate the ordinary form of galvanometer or ammeter.

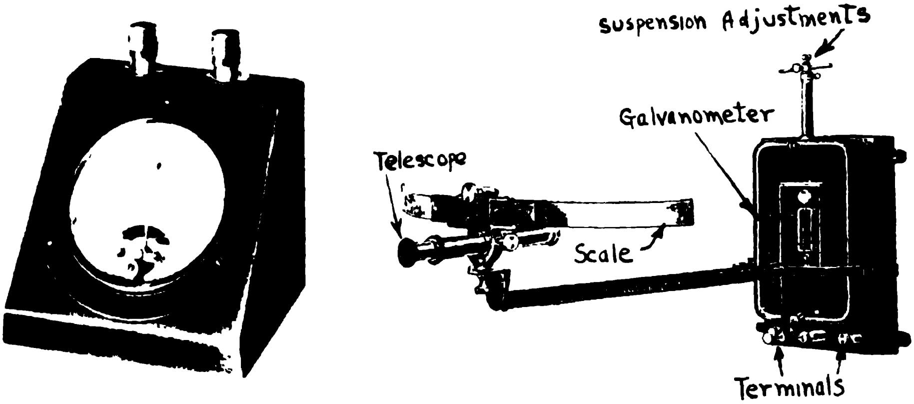


Fig 135—Left A modern Weston galvanometer built in portable form with the Weston movement

Right A laboratory type of reflecting D'arsonval galvanometer used for measurement of small currents or voltages This same instrument in ballistic form is used to measure momentary currents and voltages

196. The Weston movement: About 1885 Dr. Weston set about to improve the D'Arsonval galvanometer and reduce it to a form which would meet all conditions of accuracy, ruggedness, portability, compact size, etc., required for electrical measuring instruments which were needed at the time in connection with the development of electric lighting systems and electroplating. The so-called "Weston movement" so widely used today in d-c measuring instruments is the result of his work. He retained the basic idea of the stationary permanent magnet and moving coil, but introduced several refinements of construction which eliminated most of the objections to the old D'Arsonval galvanometer. A description of the Weston movement follows:

A very strong, carefully aged, horseshoe permanent magnet M has two soft iron pole pieces P, fastened to it by screws, as shown at (B) of Fig. 136. The magnet is hoop-shaped at the top in order to obtain a long air gap with consequent reduced magnetic leakage between the pole legs. The stationary soft iron core C, is supported by a screw passing through the brass front cross strip B, extending across the pole pieces. The iron core is smaller in diameter, than the bore of the pole pieces, so a

small annular air gap is left between them. In this air gap is a very powerful uniform, radial magnetic field as shown. Since the field is uniform and radial, the instrument has a uniform scale; that is, equal divisions at any point on the scale represent equal changes of current or voltage.

The movable coil shown at (C) consists of a light alumium-alloy rectangular form L, on which is wound many turns of very fine insulated copper wire, W, through which is passed the current (or a définite fractional part of the current) which is to be measured. This coil is provided, above and below, with hardened steel pivots which rest in cup shaped sapphire jewel bearings. It is mounted so it may turn on these pivots, in the unvarying magnetic field existing in the air gaps between the pole pieces and the iron core, as shown at (A). The current is conveyed to and from the coil through two light spiral hair-springs S, (similar to those in a watch) which perform the additional function of always returning the coil to a definite zero position and of exerting a reacting or restoring force whose magnitude is directly proportional to the angular deflection of the coil from the zero position. These two springs are

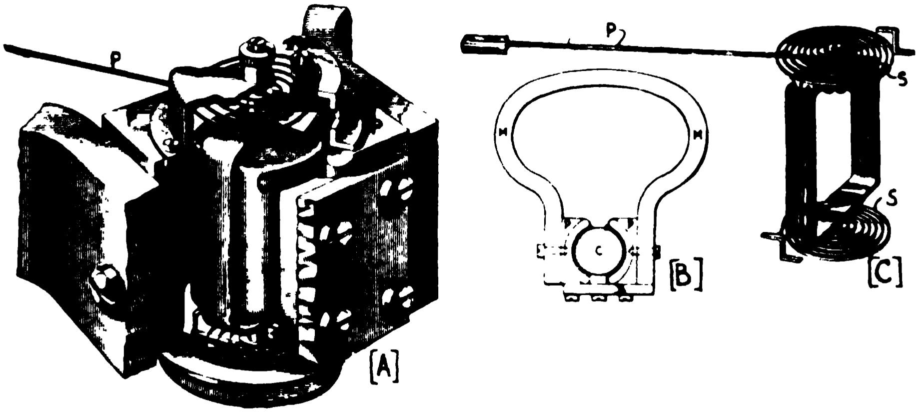


Fig 136—(A) Assembled Weston d-c meter movement A portion of the permanent horse-shoe magnet has been cut away at the left, to reveal the interior

(B) Permanent magnet, pole pieces and core assembled (C) Movable coil springs, pivots and pointer assembled

wound in opposite directions so that any increase or decrease in their length due to changing temperature conditions etc., will affect both an equal amount, and the effect of one in pushing the coil one way or the other is exactly balanced by the equal and opposite effect of the other, so that no change takes place in the position of the movable coil.

Fixed to the coil is a long hollow alumium pointer P, with a flattened knife-like end which moves over a scale which has been graduated during the calibration of the meter at the factory, when its readings were compared with those of a standard precision meter through which the same current was sent. The weight of the pointer is usually balanced by a "balancing nut" which can be moved nearer or further from the pivot. As we shall see, the scale may be calibrated to read amperes, milliamperes, volts, millivolts, etc., depending on what the meter is constructed to measure. The "zero adjuster" is attached to the outer end of the spring, and projects up through the glass in the form of a slotted screw head. When the adjustment is made the spring is rotated slightly either clockwise or counter-clockwise until the pointer is directly over the zero mark.

The entire movable coil assembly is made extremely light and the jewelled bearing have very little friction, so that it requires very little current through the coil to deflect it and the pointer around to full scale position The number of amperes through the coil required to deflect it around to "full scale" or end position is a measure of the "sensitivity" of the meter. The less current required to do this, the

more sensitive is the meter. A meter is made sensitive by using a very strong permanent magnet, a small air gap, a very light coil, and a large number of turns of fine wire on the coil. Instruments of this type usually require between 5 and 20 milliamperes, usually averaging around 15 milliamperes, for full scale deflection of the pointer.

The thin aluminum coil frame makes the instrument "dead beat" due to the opposing eddy currents set up in it when the coil is moving. Since the eddy currents are set up only when the coil and frame are moving, the eddy currents have the effect of damping or retarding any motion of the coil and needle, thus bringing it quickly to rest at the proper point when the current is turned on, and permitting the reading to be taken immediately.

A small portable galvanometer of this type used for measuring very small currents or voltages is shown at the left of Fig. 135. The two terminals are at the top and the instrument is arranged to read currents flowing through in either direction. In instruments designed for great accuracy, a mirror is often set in the scale card as shown in the meters in Fig. 139. Thus if the observer stands directly over the instrument in such a position that the pointer either completely covers its image in the mirror, or appears to be midway in the image, error due to *parallax* or reading of the deflection sidewise, is avoided because the line of vision then coincides with the pointer and its image in the mirror. When reading meters which do not have this mirror, the observer should be careful to keep his eye *directly over* the needle.

The Weston movement just described eliminates all of the objectionable features which are present in the old form of D'Arsonval movement. The rigid mounting of the coil in jewelled bearings makes the instrument rugged, compact, easily portable and very accurate. Of course the permanent magnet in any instrument of this type must not weaken even over a period of years, for any such change will weaken the attractive force for the movable coil and thus make the instrument read low. The permanent magnets of high grade instruments of this type are carefully aged to prevent this. Instruments should be handled carefully, for shocks or jars will tend to weaken the magnet and cause inaccuracy in the readings Modern electrical instruments represent the finest skill in precision manufacturing. They are built as delicately and as accurately as a watch and should be handled just as carefully. The student is urged to carefully examine the working parts of a high-grade galvanometer, ammeter, or voltmeter. When properly cared for, the readings of instruments of this type may be relied upon to be correct to within a few tenths of one per cent.

197. D-C Ammeters and shunts: We have mentioned several times that the moving element consisting of the coil frame, coil winding, pivots, springs and pointer must be very light to reduce friction in the bearings. An idea of the remarkable lightness achieved in these units may be gained from the fact that in one type of portable Weston combined voltmeter and ammeter, the entire movable system (see C of Fig. 136) weighs less than .007 ounces although consisting of 16 separate little parts. Since the wire wound on such a moving element must be fine and light, it is evident that the movable coil cannot carry very much

current without undue heating. The movable element in this form of meter is rarely allowed to carry more than about 0.05 ampere. Thus for ammeters or milliammeters designed to measure currents up to about this value the moving coil is connected directly in the circuit, and carries the full circuit current as shown at (A) of Fig. 137. The reading of the meter is of course directly proportional to the current or (number of electrons per second) flowing through the circuit and the moving coil. An actual Weston meter movement is shown in Fig. 141.

If the meter is to be connected into circuits carrying more current than this, it is evident that we must either increase the size of the wire on the movable coil proportionally to take care of the larger current with-

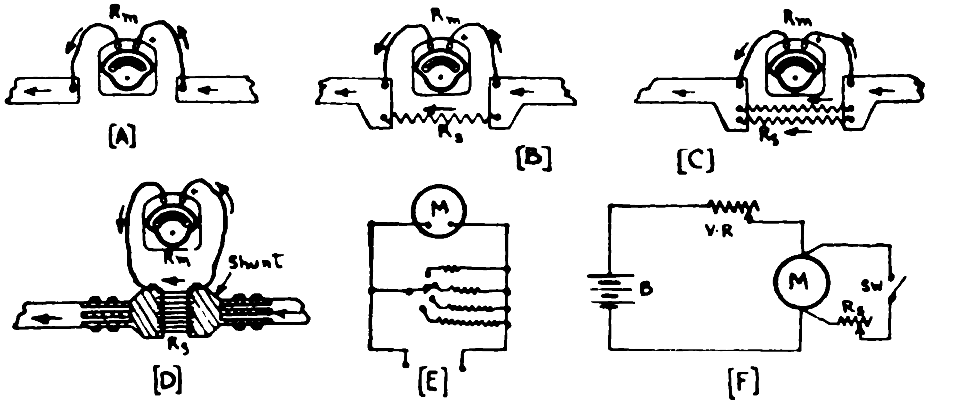


Fig 137—How shunts are connected to carry a definite fraction of the total current in a circuit, permitting the use of an ordinary galvanometer movement as an ammeter to measure large currents

out undue heating, or else we must allow only a definite fraction of the total current of the circuit to go through the meter coil, as shown at (B). The former method is impractical for it would result in a clumsy, heavy, movable coil and greatly increased inertia and bearing friction. The latter method is the one used in ammeters. The current is divided, a certain definite part of it flowing through the movable coil and the rest "shunted" around the coil by means of a low resistance "shunt" connected across it. The action of the meter with the shunt may be explained as follows:

At (A) of Fig. 137, the only path for the current is through the moving coil of the instrument. If the current to be measured is greater than the wire on the moving coil can safely carry, part of the current can be "shunted" or allowed to flow through the parallel *shunt* resistor R_s as shown at (B). Suppose the resistance R_s of this shunt is just equal to the resistance R_m of the moving coil of the meter; then, of course, just half of the total current will go through this shunt and half will go through the meter coil, and all we have to do is multiply any reading of the instrument by 2 to determine the total current. If we carried this further and added another similar shunt as at (C) the instrument reading would represent 1/3 of the total current. We might continue this indefinitely, adding any number of equal shunt resistors in parallel and thereby making the current actually flowing through the coil less and less

In practice, a single shunt resistor of the proper resistance value and current carrying capacity is connected across the moving coil for each particular current range of the ammeter. The shunts are usually made of Manganin alloy since this has a very low temperature coefficient of resistance and therefore the heat developed by the flow of current through the shunt will not change its resistance appreciably. Where the instrument is to be used to measure large currents, the shunt is constructed in multiple blade form with several strips firmly soldered into a block at each end, and having air spaces in between them for cooling, as shown at (D) of Fig. 137. The current which a shunt is to carry chiefly determines its physical size, because enough metal and surface area must be provided to prevent overheating, and at the same time the resistance must be high enough to allow a suitable portion of the current to flow through the movable coil of the instrument. When the current is greater than about 30 amperes, it is not practical to construct an instrument with a self-contained shunt, because the instrument itself would become so large as to be unwieldy, the heat developed in the shunt is not readily dissipated, and besides, the path of the current conductors would have to be more or less indirect in order to reach the instrument. It is much more convenient, therefore, to construct the shunt separately, provide it with suitable terminals and connections, and insert it by cutting the main circuit conductors (or bus bars as they are called) at any convenient point. The indicating instrument is then connected across the shunt by means of a set of flexible leads whose resistances are measured and adjusted exactly so as to form part of the instrument. These should never be cut or lengthened, as their resistance would then be changed.

For ammeters of medium range up to about 30 amperes, the manufacturer puts the shunt inside of the instrument and calibrates the scale so that it correctly indicates the *total current* without any need for further calculations. Most ammeters used in radio work have the shunts enclosed within the instrument case.

198. Use of ammeters: From the foregoing it is evident that a d-c ammeter really consists of a portable type of D'Arsonval galvanometer with a suitable shunt connected across it, and a scale calibrated in amperes. The fine wire on the movable coil only carries a definite small fraction of the total current, which is being measured.

Ammeters are used in all branches of electrical work and are designed to measure small currents of a few thousandths of an ampere (milliampere) as well as currents of thousands of amperes. In radio work, low reading ammeters are commonly used to measure the currents in the filament circuits of the vacuum tubes. Ammeters used to measure the plate currents of these tubes are called *milliammeters* (one milliampere equals 1/1000 ampere), because their scales are marked to read the current in milli-amperes. The only difference between a d-c ammeter and d-c milliammeter is in the size of the shunt employed.

The ammeter or milliammeter must *always* be connected in *series* with *either* side of the line, as shown at (A) of Fig. 137. When connecting an ammeter in a circuit, it is necessary to open one side of the line and connect the ammeter so the current flows *through* it. The instrument should have a range sufficiently high to carry the current flowing. Remember that the ammeter must always be connected in *SERIES* with *one side* of the line. Never connect an ammeter *across* the line, for since it has a very low resistance, the e.m.f. across the line would send a heavy rush of current through it and burn it out.

199. Extending the range of d-c ammeters and milliammeters: It is often desired to increase the range of a d.c. ammeter or milliammeter

on hand, in order to save the cost of a new instrument of larger range This may be done by connecting an additional shunt resistor across the terminals of the meter to shunt a portion of the total current around it. Thus consider in (A) of Fig. 137, that the meter on hand (whether it already has a self-contained shunt in it or not does not make any difference) has a range of 0-1 milliamperes. Suppose we want to extend its range to 10 m.a. Then a shunt R_s must be connected across it such that the moving coil of the *meter* will carry 1/10 of the total current and the *shunt* 9/10, or the shunt resistance will be 1/9 of the meter resistance. If the meter resistance is 27 ohms for instance, the shunt resistance required to make a 0-10 milliammeter of it would be, $1/9 \times 27 = 3$ ohms.

In general let us suppose the meter considered has a resistance of R_m ohms and let R_s be the resistance of the additional shunt to be connected across it to increase its range. Let I_m be the original maximum scale reading (in amperes or milliamperes) of the instrument Let I, be the desired new maximum reading (correspondingly in amperes or milliamperes). Then:

$$\frac{I}{I_m} = N = \text{multiplying factor}$$

$$\text{and } R_s = \frac{R_m}{N-1}$$

Example: A milliammeter having a range from 0-50 milliamperes and an internal resistance of 2 ohms, is to be converted into an ammeter having a maximum range of 10 amperes What value of shunt resistor must be connected across its terminals?

Solution: 10 amperes $= 10{,}000$ milliamperes.

$$\text{therefore } N = \frac{I}{I_m} = \frac{10{,}000}{50} = 200$$

$$\text{and } R_s = \frac{R_m}{N-1} = \frac{2}{200-1} = .01 \text{ ohm (approximately)} \quad \text{Ans}$$

Thus a shunt resistor of .01 ohm must be connected across the meter This should be of a size able to carry the current without undue heating All readings as read on the old scale of the meter must now be multiplied by the multiplying factor N, (200 in this case) to obtain the correct reading in milliamperes.

A number of shunts may be connected across a meter and controlled by a low resistance contact switch, so that any one of them may be put in the circuit at a time. This arrangement is shown at (E) of Fig. 137.

It is evident from the above problem, that in order to calculate the value of R_s by this method, the exact value of the internal resistance of the meter must be known. This information can be obtained from the manufacturer of the meter. The resistance of most small 2 inch and 3 inch diameter type milliammeters is in the neighborhood of 20 to 50 ohms.

The approximate resistance values of the Model 301 Weston microammeters and milliammeters, and corresponding Jewell meters, are given in

the table below to aid in calculating the proper resistance values to be used for extending their ranges. The model 301 type instruments are probably the most popular ones used in radio work on account of their small size, low cost, and general usefulness.

TABLE OF COMMON MILLIAMMETER CHARACTERISTICS

Weston (Model 301)			Corresp. Jewell Meters	
Range Micro-Amp.	Resistance Ohms	Number of Divisions on Scale	Resistance Ohms	Number of Divisions on Scale
200	55	40	140	40
300			140	60
500	55	50	140	50
Milli-Amp.				
1.	27	50	30	50
1.5	18	75	30	75
2.	18	40	25	40
3.	18	60	20	60
5.	12	50	12	50
10.	8.5	50	7	50
15.	3.2	75	5	75
20.	1.5	40		
25.	1.2	50	3	50
30.	1.2	60		
50.	2.0	50	1.5	50
100.	1.0	50	.75	50
150.	.66	75	.5	75
200.	.5	40	.37	40
250.	.4	50		
300.	.33	60	.25	60
500.	.2	50	.15	50
800.	.125	40		
1000.	.1	50		

Courtesy Aerovox Research Worker

If the meter resistance is not accurately known, the exact value of shunt resistance required may be found in another way as shown at (F) of Fig. 137.

Suppose we desire to calibrate a 10-milliampere meter so that it will read up to 50 milliamperes. We would connect a battery, B, as indicated on the diagram, in series with a variable resistance, V.R., so as to limit the current passing through the meter (without a shunt) to 10 milliamperes. The resistance would be varied until the meter read exactly 10 milliamperes and then the resistor R, (the shunt) would be switched across the meter and its resistance altered until the meter read 2 milliamperes. Under such conditions (with the shunt connected), a reading of 2 milliamperes on the meter would mean that 10 milliamperes were actually flowing through the circuit. Likewise, full scale deflection would indicate a 50-milliampere flow although the needle pointed only to 10 milliamperes. The same procedure would be followed in shunting any instrument, i.e., setting up a circuit which will pass sufficient current to give a maximum deflection on the meter, then shunt the meter and reduce it a definite amount such as one half, one third, or one fifth, then, in order to determine the actual current flowing in the circuit with the shunt connected, it is merely necessary to multiply the meter reading by 2, 3, or 5, depending upon how much the original deflection of the meter was reduced by the shunt.

Resistances selected as shunt multipliers (or as series multipliers for voltmeters) should be of the precision type manufactured especially for

the purpose (see Fig. 143) and should be constructed to maintain their resistance unchanged over a long period of time. They should be accurate in value, and should be wound with wire such as Manganin, Chromel, Nichrome, or Constantin, which have very low temperature coefficient of resistance, so that the resistance does not change appreciably with change of temperature. They must be of a wattage rating sufficient to insure cool operation. Also in connecting a new shunt resistor of a certain value, care should be taken to have the connecting wires of low resistance so that no appreciable resistance will be added by them. This means that short thick copper wires should be used for connection of the shunt to the meter and that all connections should be well made. In commercial meters, the connecting cables have already been considered as forming a part of the shunt resistance, so they should never be altered in any way.

200. Hot wire ammeters: The heating effect of electric current is employed in another form of ammeter called the *hot wire* ammeter. This type of meter is frequently used in radio work, since it will operate equally well on direct current, or alternating current of any frequency (the heating effect of an electric current being independent of the frequency). The fundamental arrangement in this form of meter is shown at (A) of Fig. 138.

The platinum wire D C passes around pulley K and is held taut by spring S acting on insulating block B. The current to be measured flows only up through the

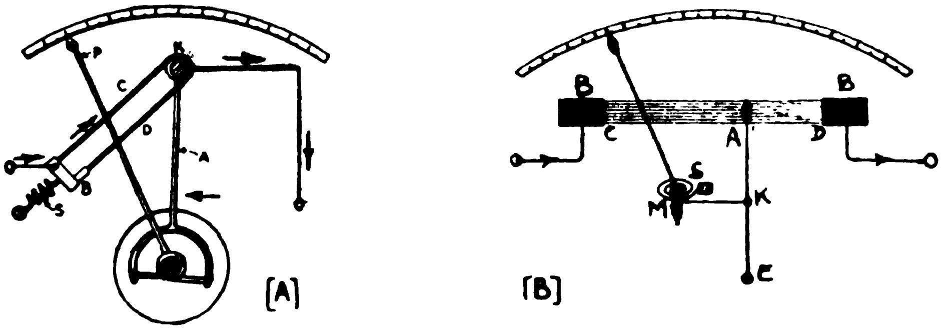


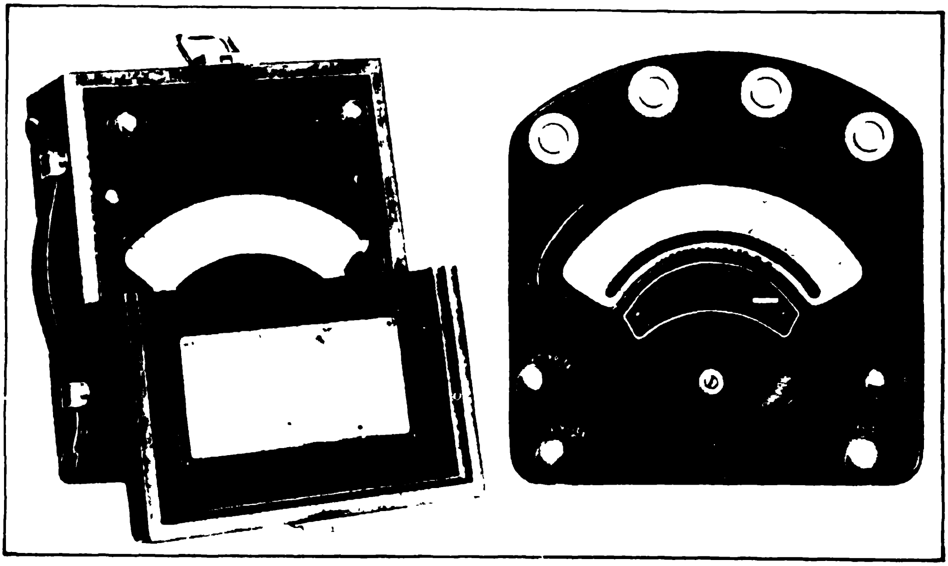
Fig 138—(A) A form of hot-wire ammeter used for measuring small current
(B) A hot-wire ammeter used for measuring larger currents

branch C of the wire as shown, and consequently that branch heats up due to the passage of current, and lengthens. The slack is taken up by the pull of spring S, causing a slight clockwise rotation of the pulley K, which causes arm A (pivoted at K) to swing to the left. This arm has two prongs at its lower end, between which a silk thread is stretched after looping itself around shaft at the lower end of the pointer P. The slight expansion of the wire is thus magnified by the mechanism, to that a large scale reading is obtained.

When large values of current are to be measured, a shunt is provided to divide the current flow. An inductive shunt with even one-half turn of wire cannot be employed because if the meter is used to measure current at *radio frequencies* (above 20,000 cycles per second), the impedance of the shunt would vary with

each change of frequency since $X_L = 2\pi fL$. Consequently, hot wire meters for large currents are constructed as shown at (B) of Fig. 138. Several resistance wires C D, are stretched in parallel between large copper blocks B B. The wire A E is attached to wires C D. A silk thread is attached to A E at point K and then wound around shaft M, in such a direction that it will work against spring S, which would normally cause the pointer to move to the full scale position. However, by means of the thread it is normally held in the zero position. When current is flowing through C D it expands, releasing the pull of the thread and allowing the pointer to move across the scale. The stronger the current, the more the wire expands and the further the pointer moves over the scale.

The type of hot wire ammeter described above is relatively slow in its operation and the wire is affected by changes in room temperature and



Courtesy Weston Elect Inst Co

Fig 139—A portable 0-2 thermo-milliammeter is shown at the left At the right is a portable precision type d-c volt-ammeter having three current ranges and three voltage ranges Its circuit diagram is shown in Fig 145

has a tendency to stretch when no current is passing through it. This makes it necessary to reset the needle to zero almost every time the instrument is to be used. The divisions on the scale of a hot wire ammeter are not uniformly spaced, since the heating effect and movement of the needle depends on the square of the current (I^2R) flowing through the hot wire. The divisions near the zero end are crowded more than at the high end, as shown in the meter at the left of Fig. 139. This type of instrument is being largely superseded by instruments operating on the thermo-electric principle. This type will now be described.

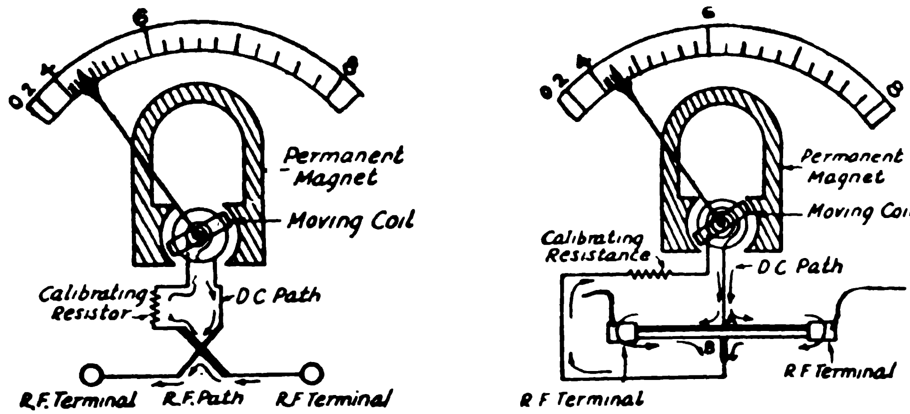
201. Thermo-couple instruments: In the *thermo-couple* ammeter or galvanometer, the sensitive element is a junction of two dissimilar metals. When two dissimilar metals are joined together and the junction

heated, a voltage is generated which is proportional to the difference in temperature between the heated junction and the other ends of the wires.

Experiment: The principle of the thermo-couple can be illustrated by twisting together one end of an iron or German-silver wire and one end of a copper wire. The other ends of the two wires are connected to a low reading d-c milliammeter and the twisted joint held over a gas flame. The milliammeter needle will move, showing that an e.m.f. and resulting current is produced by heating the junction of the two dissimilar metals. If the flame is removed and the junction is allowed to cool slowly, the milliammeter reading will drop slowly.

It is also true that when a current flows across the junction of two different metals, some heat is produced. With some combinations of metals, this effect is noticeable even with very weak currents.

Parts (A) and (B) of Fig. 140 show two methods of using the principle of generating an e.m.f. by a thermo-couple, in connection with a



(B)

Fig. 140—The principle of operation of thermo-couple instruments
(A) Single thermo-couple instrument for measuring small currents
(B) Compound thermo-couple instrument for measuring larger currents

D'Arsonval movement to measure current of any frequency. These instruments are used more particularly for measuring radio-frequency currents.

The construction shown at (A) is employed where the amount of current to be measured is relatively small, usually not to exceed one half ampere. Two small wires of dissimilar metals are electrically welded together at the center. The radio-frequency current to be measured, passes in through one wire and out through the other, heating the wires and the junction. The remaining ends of the wires are connected through a calibrating resistor to the terminals of the moving coil of the instrument. The heating effect of the radio-frequency current passing through the junction of the dissimilar wires causes a direct current e.m.f. to be generated, which in turn results in a flow of direct current through the movable-coil circuit of the instrument, as shown in the illustration.

The heating effect is proportional to the square of the radio frequency current being measured, whereas the voltage generated across the junction is proportional

to the temperature. Therefore, the motion of the pointer over the scale will increase approximately proportionally to the square of the radio-frequency current passed through the thermo-couple. Because of these factors, the instrument has a scale which is crowded at the lower end and more open at the upper end. This makes it necessary to purchase instruments of such a capacity that the average current to be measured will cause a deflection over the "open part" of the scale. Radio-frequency ammeters of this type are not especially accurate below a quarter of the full scale range, because the divisions are crowded at the lower end.

Where the radio frequency current to be measured exceeds approximately one half ampere, it is customary to use two dissimilar wires connected in parallel as far as the radio-frequency is concerned, but connected in series as far as the thermo-electric effect is concerned. This system of connections is shown at (B) of Fig. 140. The heavy line represents one type of metal and the thin line another. Manganin and "Advance" wire are used It will be noted that the voltage produced at the junction "A" is in the same direction as the voltage produced by junction "B", and they are in series so far as the d-c path is concerned, so they add together. This results in not only a higher thermo-electric voltage, but also much greater current-carrying capacity

Most thermo-couple instruments are designed for a d-c voltage across the moving coil at full scale, of between 15 and 25 millivolts. In all cases they are calibrated by adjusting a small calibrating resistor connected in series with the moving coil

This permits of re-calibration of the meter without any need for the adjustment of the thermo-couple or moving coil.

The usual difficulty encountered with thermo-couple radio-frequency instruments is the burning up of the thermo-couples by current overload. This seldom results in any damage being done to the movement and the trouble can be corrected simply by replacing the damaged thermo-couple with a new one. Most manufacturers of instruments of this type will sell the thermo-couples separately so that the customer can make his own replacements. They are usually sealed in a vacuum in a glass tube.

When replacing the thermo-couples, it will usually be necessary to adjust the resistor connected in series with the moving coil in order to re-calibrate the instrument. Calibration can be made with 60-cycle current, as the reading of the instrument is the same on radio frequencies as it is at 60 cycles.

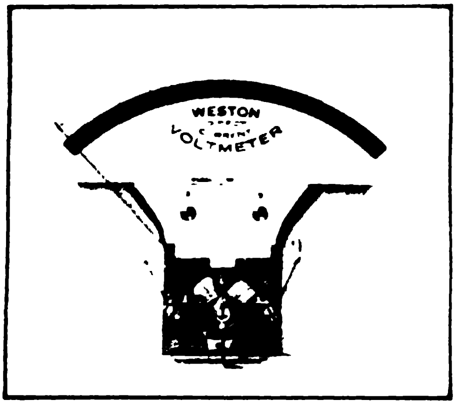
The range of a thermo-couple instrument can be changed by soldering a shunt made of a short piece of copper wire across the thermo-couple lugs. If it is necessary to double the capacity of the instrument, the pointer should be brought to full-scale reading by means of 60-cycle a-c. A shunt should then be soldered between the brass block carrying the thermo-couple, and adjusted so that the instrument reads one-half the full scale value. The current passing through the instrument then will be represented by the reading of the instrument multiplied by 2.

Shunts on radio frequency instruments always should be as short as possible, and placed parallel and close to the thermo-couple. If they are placed outside the instrument case, the instrument will not read exactly the same on radio frequencies as it does on low frequencies.

Thermo-couple instruments can be used in d-c circuits as well as in a-c circuits of any frequency. The reading is not altered by the frequency of the current.

202. Direct current voltmeter: A voltmeter is used to measure the difference of electric pressure between two points in an electric circuit. This difference of electric pressure or potential is commonly called "voltage" or "voltage drop". Voltmeters are used extensively in all kinds of electrical work, and are always connected "across," or "in parallel with," the source of voltage.

If a milliammeter were connected directly across the line, the e.m.f. would send a strong current through the fine wire, low resistance, moving coil and burn it out. To prevent this, a *high fixed resistance* is connected in series with the moving coil, as shown at (A) of Fig. 142. The milliammeter movement can then be connected across the line in series with this resistance and be used to measure voltage, since the current flowing through the coil, and therefore the turning force at any instant, is proportional to the voltage applied across the terminals of the instrument, $(I=\frac{E}{R})$. A voltmeter is simply a galvanometer or milliammeter movement (Fig 141) connected this way and having its scale graduated in volts instead of milliamperes. Whenever space is available the series resistor is contained within the case of the instrument. The series resistor is considered to be part of the voltmeter. Most voltmeters have a relatively high resistance, so they take a very small current from the line.



Courtesy Weston Elect. Inst. Co

Fig. 141—A typical Weston d-c movable-coil system. When a series resistor is added to this unit, it becomes a voltmeter (as marked). When a shunt is connected across its terminals, it becomes a milliammeter or ammeter

Suppose the galvanometer movement in the voltmeter of (A) in Fig. 142 is so constructed that its pointer deflects over the full scale when 1 milliampere flows through the coil. Let us assume this is to be built in the form of a voltmeter having a range of 150 volts. Then enough resistance R, must be connected in series with the coil so that when the voltage across the terminals of the meter is 150, exactly 1 milliampere will be flowing through the resistor and coil, and the pointer will be deflected to the end of the scale.

By Ohm's law. $E=I\times R$.

1 milliampere equals .001 ampere; therefore since $E=I\times R$, $150=.001\times R$

$$\text{from which } R=\frac{150}{.001}=150{,}000 \text{ ohms.}$$

The symbol R_m is usually emplyed to designate the *total resistance* of the meter, but since the resistance of the moving coil is very small compared to the series resistance R, R_m is taken as being the same as the series resistance in most practical problems. The scale of the above instrument would be graduated uniformly in volts, with the maximum at 150 volts.

The high resistance is usually placed inside the voltmeter case, and connected in series with the coil. It is called a *multiplier resistance*. When space is not available, external resistors or "multipliers" are used.

D'Arsonval voltmeters sometimes cause trouble due to open circuits in the multiplier or series resistor. These resistors are wound of the thinnest resistance wire to be had, and are easily damaged by mechanical abuse or by allowing the multiplier to get wet If the multiplier is made

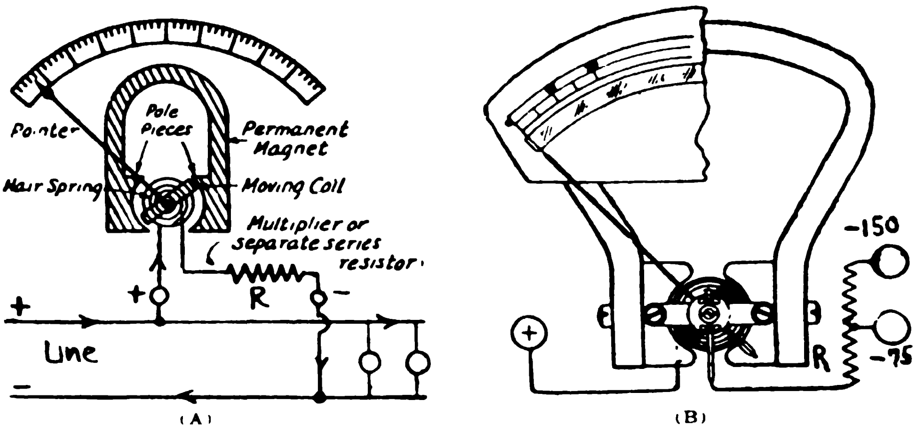


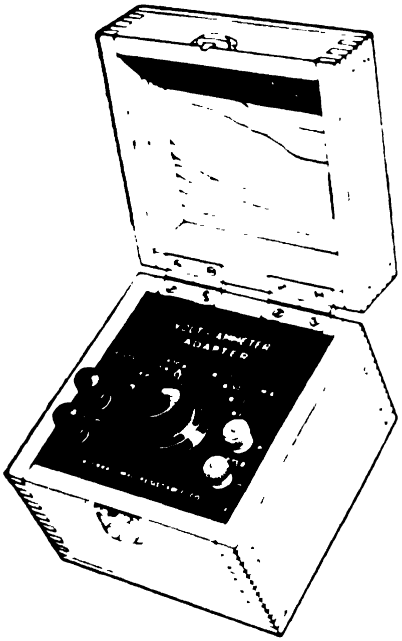
Fig. 142—The general arrangement of a d-c voltmeter In addition to the basic moving coil assembly there is a resistor connected in series with the coil This "multiplier" resistor determines the range of the meter At (B) is shown the use of a tapped multiplier resistor to obtain a voltmeter having two ranges, 75 volts and 150 volts

up of sections and becomes open-circuited, the open section can usually be located and bridged, without the necessity of sending the instrument back to the manufacturer.

It is common to build voltmeters so they have more than one range. This is done by simply tapping the series resistor at suitable points for the low voltage ranges. Thus in the voltmeter considered above, the total series resistor is 150,000 ohms. If a tap were made at the center of this and brought out as shown at (B) of Fig. 142, a voltage of only 75 volts applied between the common terminal and the tap at this 75,000 ohm section, would send a current of $I=\frac{E}{R}=\frac{75}{75{,}000}=.001$ ampere through it, and would produce full-scale deflection. Thus, this would provide a 75-volt range for the instrument in addition to the 150-volt range. Three bind-

ing posts would be arranged on the instrument as shown. In order to have the current flow through the coil in the proper direction, the binding post marked + is connected to the positive wire of the line, and either of the other posts are connected to the — side of the line. A small push-button switch is often provided in portable instruments so that the voltmeter circuit may be closed only when the measurement is being taken.

When using a double-range voltmeter or ammeter, care should be taken not to accidentally apply too much voltage or current to the low-scale terminals, since burn-out of the moving coil may result. If the voltage or current in the circuit are not known, the high-reading range should



Courtesy International Resistor Co

Fig 143—Left. A multiplier and shunt box which enables one to make either a 4-range milliammeter or a 4-range voltmeter from a single low-reading milliammeter

Right. A precision wire-wound multiplier resistor for increasing the ranges of voltmeters or making voltmeters of any desired ranges from milliammeters

always be tried first. Then if the reading is less than the highest value of the lower reading range, that range should be used for the final test

203. Increasing d-c voltmeter ranges: The range of any voltmeter may be increased to any practical limit by inserting a "multiplier" resistance in series with the voltmeter. The resistances should be of the precision type, and permanent in value, as in the case of the resistors used for ammeter shunts. A resistor made especially for this purpose is shown at the right of Fig. 143. At the left of Fig. 143 is shown a combined shunt and multiplier box having precision adjustable resistors which enable one to make either a milliammeter having four current ranges, or a voltmeter having four voltage ranges, from a single low-reading milliammeter. A multiplier of this type is of considerable value in radio test work, in that it does away with the necessity of having a num-

ber of milliammeters and voltmeters of different ranges for various tests and measurements.

The customary method of increasing the range of a d-c voltmeter is to connect a high resistance in series with it.

Let R_v=resistance of voltmeter in ohms, or, if ohms-per-volt is given, then

R_v=ohms-per-volt × original full-scale range of meter, in volts.

V_1=original full-scale range of meter, in volts.

V_2=desired new maximum range, in volts.

then $\frac{V_2}{V_1}$=N=multiplying factor.

R_m=resistance of multiplier to be connected in series with the meter, in ohms.

$$\text{Then}\quad R_m=(N-1)\times R_v$$

The ratio $\frac{V_2}{V_1}$=N is the "multiplying factor" by which any reading on the old voltmeter scale is to be multiplied in order to determine the true voltage being measured.

Problem: The range of a voltmeter having a range of 150 volts and having a resistance of 150,000 ohms is to be increased to 750 volts. What multiplier resistance must be connected in series with it?

Solution: $N=\frac{V_2}{V_1}=\frac{750}{150}=5$=multiplying factor.

and $R_m=(N-1)\times R_v=(5-1)\times 150{,}000=600{,}000$ ohms. Ans.

Each reading taken on the voltmeter according to its old scale, must be multiplied by 5 to get the true voltage.

A series resistor properly tapped can be used to provide a number of voltage ranges, as shown at (B) of Fig 142. If the resistance of the voltmeter R_v is not known, it can be found by connecting it across a source of potential, within the range of its scale, with a milliammeter connected in series with it to indicate the current drawn by the meter from the line. The resistance of the voltmeter is then equal to

$$R=\frac{\text{Reading of the voltmeter (volts)}}{\text{Reading of the milliammeter (M.A.)}}\times 1{,}000.$$

204. Making d-c voltmeter from milliammeter: A voltmeter is simply a galvanometer in which a coil of high resistance is connected in series with the moving coil. Therefore it is a simple matter to convert a d-c milliammeter into a voltmeter by connecting a resistor of the proper value in series with it. To make a d-c milliammeter into a d-c voltmeter:

Let I=original maximum full-scale range of meter, in milliamperes.

V=desired full-scale range of meter, in volts.

R_m=resistance of multiplier required, in ohms.

$$\text{Then} \quad R_m = \frac{1{,}000 \times V}{I}$$

Example: A milliammeter having a current range of one milliampere and a resistance of 25 ohms is to be converted into a voltmeter having a range of 750 volts, by connecting a "multiplier" resistor in series with it. What must be the value of this resistor?

Solution: $R_m = \frac{1000 \times 750}{1} = 750{,}000$ ohms. Ans.

It will be noticed that the formula above neglects the resistance of the moving coil, since this is usually very small compared to that of the series resistor when high voltage ranges are to be obtained. If the voltmeter range is to be below about 10 volts, R_m in the above formula should be considered to be equal to the actual resistance of the meter plus that of the added multiplier resistance.

205. High-resistance voltmeter. The function of a voltmeter is to measure the difference of potential existing between two points in a circuit. It should not influence in any way, the circuit or device across

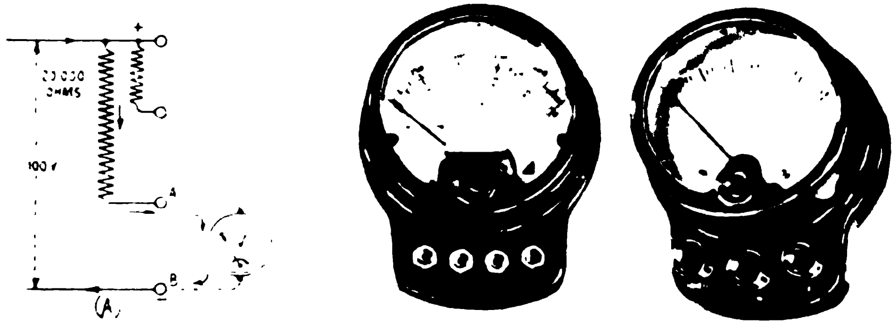


Fig 144—(A) Connection of a voltmeter to the output circuit of a B-eliminator
Middle: A 3-range d-c high resistance voltmeter having a resistance of 1000 ohms per volt
Right. A 2-range a-c voltmeter. These instruments are very useful in radio tests and service work

which the difference of potential exists. Since every voltmeter will draw some current from the circuit across which it is connected, this current really puts a load on the circuit or device being measured. If the circuit or device has quite some resistance, the meter current flowing through it may produce an additional appreciable fall of potential through it. In this case, the voltage indicated by the meter, is really *lower* than the actual voltage which exists across the circuit normally when the meter is not connected to it.

Thus in (A) of Fig. 144, suppose we are to measure the output voltage across the B battery eliminator circuit at A - B. An e.m.f. of say 100 volts is applied to the circuit by the rectifier tube, and a resistor of 20,000 ohms is in series with the voltage tap we are connecting the voltmeter across. Suppose the voltmeter has a

range of 150 volts and a total resistance of 1,000 ohms. The current actually flowing through the resistor and the voltmeter may be found by Ohm's law. Since the 20,000 ohm resistor and the voltmeter resistance are now in series we have:

$$I = \frac{E}{R} = 100 \div (20{,}000 + 1{,}000) = .0048 \text{ amperes, or } 4.8 \text{ milliamperes.}$$

This current flowing through the 20,000 ohm resistance causes a voltage drop across it of $E = I \times R = .0048 \times 20{,}000 = 96$ volts.

The voltage actually recorded on the meter then, is the difference between the applied circuit voltage and the drop across the 20,000 ohm resistor or,

$$\text{Voltage at A B} = E - (I \times R) = 100 - 96 = 4 \text{ volts}$$

Thus the meter is not indicating the true voltage of the circuit, since it is drawing so much current from the circuit that the circuit voltage drops when it is connected. The meter reads 4 volts, whereas the voltage of this circuit when the meter is not connected, is 100 volts. Of course this is an exaggerated case.

The remedy for this condition is to use a *high-resistance* voltmeter, that is, one having a high resistance connected in series with its moving coil. Suppose the meter has a resistance of 1,000 ohms for each volt range of its scale (1000 ohms per-volt), then its total resistance is $150 \times 1000 = 150{,}000$ ohms. The current drawn by such a meter from the circuit just considered would be,

$$I = \frac{E}{R} = 100 - (20{,}000 + 150{,}000) = .0006 \text{ amperes, or } .6 \text{ milliamperes}$$

and the $I \times R$ drop across the circuit resistor is,

$$E = I \times R = .0006 \times 20{,}000 = 12 \text{ volts}$$

and the voltage read at A B would be $100 - 12 = 88$ volts.

This shows that the high resistance voltmeter gives a reading of 88 volts which is much nearer the true open-circuit or no-load voltage of 100 volts than before.

Since a voltmeter having a high resistance takes very little current from the line, the meter itself must be very sensitive, that is, it must require very little current to move its coil and pointer over full scale deflection. This means that either the permanent magnet must be stronger than in the usual meter, or else more turns of wire must be wound on the moving coil to obtain the same ampere-turn effect at a smaller value of amperes. The latter method is used in the construction of high resistance voltmeters used in radio work. The moving coil has several layers of exceedingly thin copper wire in order to produce the necessary magnetic field strength. Such meters have a resistance as high as 1000 ohms-per-volt. The term *ohms-per-volt* may be understood by considering the specific case of a 1000 ohms-per-volt meter having three ranges, 7.5, 150, and 750 volts. Then the resistance in series with the 7.5-volt terminal is 7.5×1000 or 7,500 ohms; that in series with the 150-volt terminal is $150 \times 1000 = 150{,}000$ ohms; that in series with the 750-volt terminal is $750 \times 1000 = 750{,}000$ ohms.

The "ohms-per-volt" value or R_{pv} is equal to the total resistance R_t of the meter divided by the maximum voltage E_t marked upon the scale considered, or

$$R_{pv} = \frac{R_t}{E_t}$$

Voltmeters having a resistance of 1000 ohms-per-volt are used extensively for voltage measurements in radio receiver power packs. A

3-scale voltmeter for this purpose is shown at the middle of Fig. 144. Voltmeters having an ohms-per-volt value as low as 100 are used in ordinary electrical work, since the few milliamperes of current taken by the meter is not objectionable here.

It should be remembered that it is not possible to make a high-resistance voltmeter of the same range from an ordinary low resistance voltmeter by simply connecting a resistance in series with it, for this would reduce the current which flows through the meter, and would therefore reduce the deflections of the pointer. High-resistance voltmeters are built especially for the purpose, more sensitive than the ordinary low-resistance type.

206. Combined voltmeters and ammeters: For certain applications, instruments of the movable-coil type are arranged so that the same instrument may be used either as a voltmeter or as an ammeter, and successive readings of voltage and current may be made with great rapidity. Such instruments are called volt-ammeters.

The instrument shown at the right of Fig. 139 is of triple range for both voltage and current, usually designed for a maximum voltage of 150 volts, with sub-ranges for 15 and 3 volts. The ampere ranges are usually 30, 15 and 3, or 15, 3 and 1.5 as preferred. Many other combinations are obtainable.

In order to obtain a clear idea of the general layout of one of these instruments, a connection diagram is shown in Fig 145. The shunts are in series with each other, and are connected in multiple with the movable coil through a resistor and a push-button. When connected in the line, only a small part of the current flows through the movable coil, but the pointer indicates the *total current*, because the current flowing through the movable coil is always an exact fraction of the total current, and therefore, the scale is calibrated to indicate this total current which is being measured.

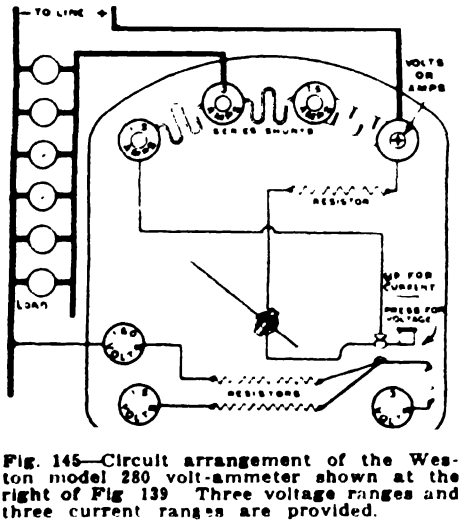


Fig. 145—Circuit arrangement of the Weston model 280 volt-ammeter shown at the right of Fig 139 Three voltage ranges and three current ranges are provided.

If the proper voltage range is connected across the line and the button is pressed, the main current continues to flow through the shunts, but the pointer no longer indicates amperes because the movable coil circuit to the shunts is opened, and when the button is fully depressed the movable coil will form part of the voltage circuit.

Since a correctly adjusted non-inductive resistor is connected with each voltage range, the one in use will indicate volts, because the current which will flow depends upon the voltage of the circuit. This instrument may, therefore, be used to give volt and ampere indications in practically instantaneous succession as the button is pressed and released.

Instead of having a single hundred and fifty volt resistor tapped at the proper resistances for each of the lower ranges, as previously explained, there are three separate resistors each capable of taking care of the voltage designated on their respective terminals. With this arrangement, if one of the resistors should become damaged, it will not affect the operation of the instrument on the other ranges.

When a separate shunt or series multiplier resistor is used to extend the range of a meter it is important to use accurate seasoned resistors designed for the purpose. The maximum per cent error in any case, is the sum of the per cent error of the moving element and the per cent error in the resistance used. A moving element that is accurate to say 2 per cent would never be more accurate than this no matter how accurate the multiplier is made. On the other hand, if the meter is of an expensive type having a moving element with a high degree of accuracy, a very accurate multiplier should be used. If closer accuracies than one per cent are required, it should be specified that the resistors which are provided, should be accurate to better than ½ per cent.

Fortunately, special wire-wound resistors of an accuracy of one per cent and less are now available commercially, as contrasted with the wider tolerances of ten per cent and more of ordinary commercial resistors. Furthermore, these resistors are thoroughly seasoned. That is, they have been aged so that no resistance changes over a period of time due to easing up of the molecular strains caused in the wire by the tension applied during winding will occur. A wire-wound resistor of this type is shown at the right of Fig. 143.

These perfected wire-wound resistors now make it possible to convert meters into multi-range instruments with every assurance of accurate reading, on all the ranges.

207. Wattmeters: In a direct current circuit, the electrical power in watts expended in the circuit, is equal to the voltage multiplied by the current in amperes. These factors can be determined simply by connecting an ammeter in series with, and a voltmeter across, a d-c circuit and taking the readings. Thus, suppose the ammeter reads 5 amperes and the voltmeter reads 110 volts; the power in watts will equal $W = E \times I = 110 \times 5 = 550$ watts.

In an alternating current circuit, the power is given by $E \times I$ only if the apparatus connected in the circuit is purely resistive in character. If the apparatus is inductive or capacitive (excepting in the case of resonance) the power factor ($\cos \theta$) must be considered, and the *true power* in watts will be equal to $E \times I \times \cos \theta$, where $E \times I$ gives the *apparent power*.

The power in either an alternating current circuit or a direct current circuit can be measured directly by a *wattmeter*. This automatically multiplies the volts and amperes together and indicates directly the instantaneous value of the *true power* in either kind of circuit, regardless of the power factor. The wattmeter is really a combination of two instruments in one, a voltmeter and an ammeter.

As shown at the left of Fig. 146, two coils are used; one is called the *voltage* or *potential* coil, and the other the *current* or *series* coil. The current coil is fixed in position since it is wound with heavy wire, and is connected in series with one side of the line just as an ammeter would be connected. The voltage or potential coil is connected across the circuit just as a voltmeter would be connected, and is mounted

inside the current coil on jewelled bearings, so it can move freely. The pointer P which moves over a suitably calibrated scale for reading, is fastened to the movable-coil.

The current coil A-A is wound with heavy wire, so as to offer very low resistance to the passage of the line current through it. The ends of this coil are brought out to two large binding posts D D. The movable coil B is the voltage coil, and is connected across the line through the high non-inductive series resistance R, and out to the two small, voltage binding posts, E E The winding of coil B consists of a few turns of very fine insulated wire The control springs C C serve as conductors for current to and from the moving coil, they also keep the pointer at zero when there is no current flowing, and oppose the movement of the coil when there is current. The pointer is provided with a threaded extension at the non-indicating end and is fitted with a balancing nut which counter-balances its weight.

The magnetic field or force produced by the stationary current coils is proportional to the current flowing through these coils and the main circuit The magnetic

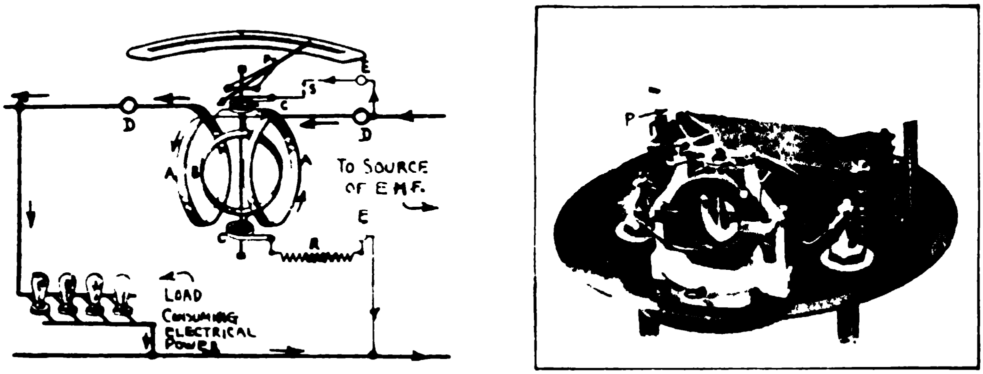


Fig. 146—Left: Construction features of an indicating wattmeter and method of connecting it in a circuit
Right: An interior view of a wattmeter with enclosing case removed The various main parts are labeled to correspond with the diagram at the left

field or force produced by the moving voltage coil is proportional to the difference of potential applied to the potential-coil terminals of the instrument; this is the voltage of the circuit to which the meter is connected. The combined action of the poles of these two magnetic fluxes, one proportional to the current in the circuit, and the other proportional to the voltage, tends to turn the movable coil clockwise, the total turning effort at every instant being proportional to the product of the *instantaneous* current and voltage, or to the watts. At the point of reading, the torque due to the magnetic action is balanced by the counter torque of the control springs, and the pointer and scale indicate the watts corresponding to the load on the circuit. The instrument may be used either on alternating or direct current circuits, since on a.c. the current in both the current and the voltage coils reverses at every alternation so the resultant direction of attraction between the poles of the coils remains the same. The student should prove this for himself by drawing the two coils and working out the direction of attraction first when the current flows through them one way and then when the currents in both are reversed. A wattmeter with enclosing case removed is shown at the right of Fig. 146.

Care must be taken to see that a wattmeter is not connected in a circuit carrying either a current or a voltage value above the maximum current and voltage rating of the wattmeter, for overheating or possible burnout of the coils will result. For example, on a particular 1500-watt instrument the maximum current rating is say 10 amperes and the maxim-

um voltage rating is 150 volts. If this instrument were connected in a circuit in which 20 amperes were flowing and an e.m.f. of 50 volts existed, the current-coil of the meter would be overloaded even though the meter would be indicating only $50 \times 20 = 1{,}000$ watts.

Also, since the voltage-coil takes some current and power from the circuit, in order that the instrument will not indicate these watts in addition to the circuit load, the voltage-coil should be connected to the circuit on the *incoming side* of the current-coil connections, as shown at (A). Then the current in the voltage coil will not pass through the current coil as may be seen by tracing the arrows indicating the current flow in these two coils Wattmeters of the type mentioned above are sometimes called *indicating wattmeters*.

208. Recording watt-hour meter: The consumption of electrical energy is paid for and based upon the *kilowatts* (1 kilowatt=1,000 watts) multiplied by the number of hours. To measure by means of a wattmeter, the electrical energy in watt-hours supplied to a device, it would be necessary to multiply the average of a number of watt readings taken during a given time, by that time expressed in hours. As its name implies, the *recording watt-hour* meter gives the total watt-hour consumption of energy directly, since it automatically multiplies the average of the instantaneous wattage indications by the time.

The recording watt-hour meter really consists of a simple type of electric motor driven by the electric energy which it is to measure (which is arranged to flow through it); its speed of rotation at any instant is proportional to the power in watts flowing through it and delivered to the power consuming device at that instant. By means of a train of gears and suitable dials, the total revolutions made by the motor over a period of time are added up and recorded, so that the total watts or kilowatts which have passed through the meter on the way to the device consuming the electrical power during that time, is recorded. Usually four dials are arranged to give the readings, one dial giving the units, the next one the tens, etc., just as on an ordinary gas-meter. The unit upon which the measurement is based and made, is usually marked on the dial-face, and would be watt-hours or kilowatt-hours.

Watt-hour meter readings are additive, so to find the amount of electrical power consumed during any interval of time, it is necessary to subtract the reading at the beginning of the period from that indicated at the end.

209. Power consumption test of radio receivers: If the power consumed by a device is to be ascertained by a short test during which the dials of the watt-hour meter would not move much, it may be found by accurately measuring with a watch, the time in minutes it takes for the aluminum disc in the meter (watching the black line on the disc) to make say 100 revolutions, then multiply the number of revolutions found, by the "constant" of the meter and by 60 and divide by the number of minutes during which the test was run. This will give the watt-hour consumption of the device for each hour. The *meter constant "K"* is the multiplying factor by which each revolution of the disc must be

multiplied to find the corresponding average watts which have passed through the watt-hour meter during the revolution. The "constant" is usually marked on the aluminum disc of the meter or on the name plate, and varies for different types and sizes of meters.

This method is often used to check the watt-hour consumption of radio receivers installed in homes, in order to find out the cost of the electrical power consumed by the receiver for each hour of operation. As the watt-hour meter already installed in the home by the electric light company may be used, no additional meter is necessary. The same method may be used for checking the power consumption of household electrical devices.

Example: A power consumption test is run on a radio receiver. The watt-hour meter disc makes 30 revolutions in 10 minutes, and the constant K, of the meter used is 0.6 watts. If power is supplied by the electric light company for 10 cents per K.W.-hour, how much does it cost to run the radio receiver for one hour?

Solution: $$\text{K. W. hours} = \left(\frac{30 \times 0.6 \times 60}{10}\right) \div 1000 = 0.108 \text{ K. W. hours}$$

Therefore, $0.108 \times \$0.10 = \$0.01$ per hour. Ans.

Watt-hour meters are often used to measure the total amount of electric power sent into storage batteries during charging. Of course they are also used by electric light and power companies to record the total amount of electric power used by each customer during the month.

210. A-C meters: The D'Arsonval ammeters and voltmeters thus far discussed have been of the magnetic type which are employed in direct current circuits. This type of meter will not function when connected in an alternating current circuit, because during one alternation the current would flow through the coil in one direction and the poles produced would tend to deflect the coil in one direction, and on the following alternation the current and poles would be reversed and would therefore tend to deflect it in the opposite direction. These alternations follow one another so rapidly that the moving element in tending to obey one impulse is almost immediately caused to move in the opposite direction by the next impulse, with the result that the indicating needle remains practically stationary, trembling slightly at the zero position. Since permanent magnet instruments cannot be used to measure alternating currents, they are generally called *direct current instruments*.

We have already seen that hot-wire and thermo-couple ammeters and milliammeters can be used to measure a-c as well as d-c but they are used mostly in circuits carrying radio-frequency currents. There are two main types of meters used in ordinary commercial low-frequency measurements. They are, the Thompson inclined-coil type and the Weston movable-iron type.

211. Thompson A-C ammeter: The Thompson *inclined coil* meter manufactured by the General Electric Company is shown at (A) of Fig. 147.

The inclined coil C through which the current passes, is shown in cross-section. It is mounted with the axis inclined to the horizontal. In the center of the coil is a vertical shaft mounted in jewel bearings and controlled by fine flat hair-springs S S. The shaft carries a light pointer at its upper end. At the center of the shaft is a vane of soft iron A, obliquely mounted.

When no current flows through coil C, the hair-springs keep it at the zero position, and the iron vane lies nearly at right angles to the axis of the coil at position "A". When current is passed through the coil the iron vane tends to turn so that the lines of force passing through it are parallel to the lines of force passing through the center of the coil as shown by the dotted line position "B". This turning of the vane and shaft against the action of the hair-springs, causes the pointer P, to move across the graduated scale from which the reading is obtained.

The coils for large sizes of instruments are generally wound with a few turns of flat insulated copper ribbon having a very low resistance.

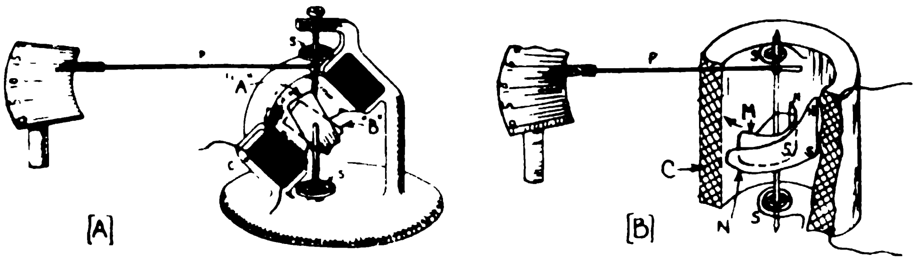


Fig 147 (A) Thompson inclined coil a-c instrument The iron vane position marked "A" is slanting toward the back from top to bottom
(B) Weston movable iron a-c instrument

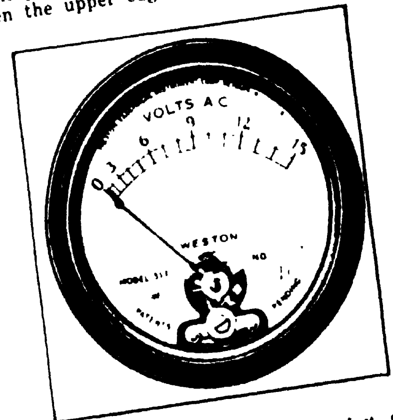
When alternating current flows through the coil, the lines of force through it will be rapidly changing in direction. Since the vane is of soft iron, and will tend to line itself up with the lines of force of the coil whether they go up through the coil or down through it, this type of instrument can be used for either direct or low-frequency (60 cycles or so) alternating current. This type of instrument does not have a uniform scale, the divisions at the lower end being more crowded than at the upper end.

212. Weston movable-iron a-c meters: The instruments made by the Weston Electrical Instrument Company primarily for measuring alternating currents and alternating e.m.f.'s, are also of the "moving-iron" type, but are so constructed that many of the defects of other solenoidal types have been eliminated.

The stationary coil of these instruments is wound with a few turns of heavy copper wire or strip when the instrument is to be used as an ammeter. In this case the coil is merely connected in series with the circuit. When the meter is to be used as a voltmeter, the coil consists of a large number of turns of fine wire, and connected in series with this coil, is an accurately adjusted high resistance. As shown at (B) of Fig. 147, the moving armature M, which lies in the center of the coil C, consists of a small piece of soft iron, semi-circular in shape, secured to a vertical shaft which rest in accurately fitted jewel bearings. A pointer P of truss construction and

of very light weight is secured to the upper end of the shaft. A small, loose fitting, thin vane (not shown) is attached to the pointer and moves in a small air compartment. The vane, as it moves in the closed air compartment like a piston in a pump, provides the damping required to prevent the pointer from oscillating, and thus makes the instrument "dead beat". An adjustable balancing weight at the non-indicating end of the pointer enables it to be accurately balanced. Situated close to the movable iron sleeve, is secured a stationary piece of curved soft iron N, triangular in shape, with the small end of the triangle rounded off as shown. This piece of iron is securely held in place, does not move, and has no physical connection to the movable iron piece on the shaft.

When the coil is connected in the circuit, the current through it sets up a magnetic field through the center and both soft iron vanes become magnetized. The upper edges of each will always have a like magnetic polarity and the lower edges will always have a like magnetic polarity, but when the upper edges are north poles the



Courtesy Weston Elect Inst Co

Fig 148—Left. Phantom view of the movement of a Weston movable-iron type of a-c instrument
Right: 2-inch diameter a-c movable-iron voltmeter used in radio work Notice the crowding of the scale at the low end

lower edges are south poles and vice versa. Therefore, there will always be a repulsion between the two upper edges, and also between the two lower edges of the soft iron strips, no matter in which direction the current is flowing through the coil, so the instrument can be used either in d-c or in a-c circuits. This sidewise repulsion tends to make the movable vane M, slide around from the fixed one N, and in doing so it rotates the shaft against the action of the hair springs. The pointer then moves over the graduated scale and indicates the volts or amperes depending on whether the instrument is constructed and connected as an ammeter or as a voltmeter. A phantom view of an a-c ammeter of this type is shown at the left of Fig. 148. A small 2-inch diameter alternating current voltmeter used in radio work for measuring the vacuum tube filament voltages in a-c electric receivers is shown at the right. Most of the a-c filament ammeters and voltmeters are of this type.

This type of instrument can be used for direct current measurement with a precision of one or two per cent. When carefully calibrated, a precision of 0.5 per cent and better can be obtained on commercial frequency alternating current. Its advantages are its simplicity, cheapness and the fact that there is no current carried to the movable element. In many of the moving-iron type instruments, the coils are surrounded by

iron laminations to shield them from stray external magnetic fields which would cause an appreciable change in their readings, since the iron armature moves in a comparitively weak field inside the coil. Movable-iron type voltmeters are not as sensitive as d-c voltmeters, that is, they require more current in the field coil to produce movement of the pointer, since the magnetic field is practically all in air. Consequently, they draw more current from the line. Movable-iron type instruments have a non-uniform scale which is closely spaced near the bottom and much more open near the upper end as shown on the meter at the right of Fig. 148. When instruments of this type are being purchased, care should be taken that their range is such that the values to be measured come in

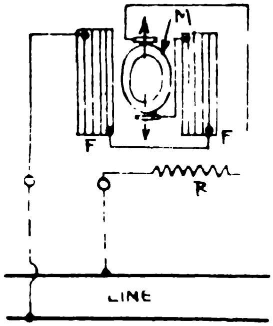
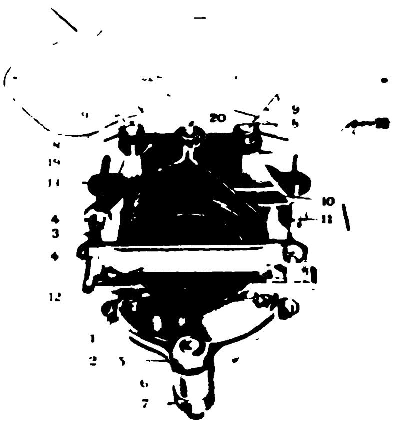


Fig 149- Left: Principle of the electro-dynamometer type of an a-c instrument



Right Weston electro-dynamometer type of a-c instrument with fixed and movable coils

the open part of the scale rather than near the lower end where it is difficult to read the instrument accurately.

213. Electro-dynamometer a-c voltmeter: Some types of alternating current voltmeters operate on the electro-dynamometer principle.

The fixed coils F F at the left of Fig. 149 are wound with fine wire and are connected in series with the movable coil M The magnetic poles produced on coils F F attract those produced on movable coil M and tend to turn it around, carrying the pointer with it. A high non-inductive resistance R is connected in series with the dynamometer to limit the current when the instrument is connected across the line The current passing through the instrument is therefore proportional to the voltage of the line it is connected across. As the deflections are nearly proportional to the square of the current flowing through. the scale is non-uniform, being crowded at the lower end. The main parts of an actual meter of this type together with the assembled unit are shown at the right of Fig. 149

The dynamometer-type of voltmeter takes about 5 times as much current from the line as a d-c voltmeter of similar rating and consumes a comparitively appreciable amount of power. As the moving coil moves in a comparitively weak field due to the fact that the magnetic field is entirely in air. this type of instrument is very susceptible to stray magnetic fields and should not be brought too near current-carrying wires, magnetic apparatus, etc. The instrument may of course be used for measuring direct current as well as for measuring alternating current.

Owing to the difficulty of leading a heavy current into a moving coil, dynamometer ammeters are not commonly made. It is not practical to use a shunt as in the case of the D'Arsonval type d-c ammeter, because alternating currents divide inversely as the circuit *impedances*. Unless the ratio of inductance to resistance were the same in the shunt as in the moving coil, the instrument would be correct at only one frequency, since the impedances of the shunt and moving coil would vary differently with change of frequency. It is for this reason that multiplier resistances are seldom used for increasing the range of alternating current voltmeters or ammeters unless they are to be used only in circuits of a single definite frequency. Dynamometer type instruments in which these difficulties are partly overcome are available, but the movable-iron type of instrument is so much simpler and less expensive, that the dynamometer type is used very little.

214. Dry plate rectifiers, and copper-oxide rectifier type meters: In many alternating current measurements commonly made in radio work it is of utmost importance that the measuring instrument used require very little current or power for its operation. An instance of this is in the measurement of the ouput signal-voltages of a radio receiver. If an ordinary a-c voltmeter were connected across the output terminals of the set, it would absorb a comparitively large proportion of the power available and the reading obtained would be far from accurate. The measurement of the alternating voltages and currents in these circuits is not always readily accomplished, as the necessary instruments are too sluggish in their movement, or require too much power for their operation. Thermocouple instruments have the first two disadvantages, moving-iron instruments have the last two, and dynamometer instruments have the first and last drawbacks.

In general, a-c meters are more sluggish than d-c meters and require a great deal more power to operate them. This last drawback is a very serious one in radio measurements, for it often happens that more power is required to swing the meter's needle than is available in the circuit being studied. We are accustomed to d-c voltmeters requiring only 1 milliampere to produce a full-scale deflection (sensitivity of 1000 ohms per volt) and know that a voltmeter consuming 10 milliamperes has a limited usefulness in most radio measurements. On the other hand, a-c voltmeters of the moving-iron and dynamometer types generally require from 15 to 100 ma. in the higher ranges and from 100 to 500 ma. in the lower ranges. The power consumption is usually several watts! Even the expensive and fragile thermocouple instruments require 10 ma. to produce a full-scale deflection.

The advantages of the low current drain of sensitive d-c instruments can be retained for measuring low a-c voltages and currents by using a suitable sensitive D'Arsonval type d-c instrument in connection with a copper-oxide type rectifier.

A rectifier is a device which offers a high resistance to the flow of current through it in one direction, and a comparitively low resistance to the flow of current through it in the opposite direction. Thus if an alternating voltage is applied to the terminals of a rectifier, current can flow through it only in one direction, so the current is a pulsating direct current. Hence we say the a-c is rectified to d-c. Several forms of rectifiers have been developed, but the most suitable, simple and inexpensive one yet found for use in rectifier instruments is known as the *copper-oxide* dry-contact rectifier. We must digress from our study of meters at this point to take up the study of dry plate rectifiers so that we may understand their operation and connections in these meters.

Types of Rectifiers: Dry-contact rectifiers include a wide assortment of devices which, though similar in structure, operate on various principles. All of them comprise a junction between two dissimilar substances, generally a metal and a crystalline

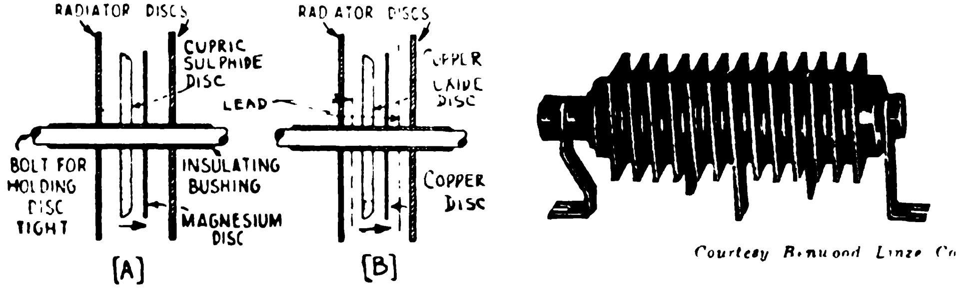


Fig. 150. (A) A single element of a cupric sulphide type of dry-plate rectifier. (B) A single element of a copper oxide type dry-plate rectifier.
Right A cupric sulphide type rectifier arranged for full-wave rectification and designed for an output capacity of 1 to 9 amps at 8 to 12 volts. This is employed in electro-dynamic loud speakers, to furnish d-c current for the field coils from the 110 v. a-c electric light line.

metallic salt which is electrically conductive. The junction offers a low resistance to the flow of current from the crystalline metallic salt to the other metal and a high resistance to the flow of current in the reverse direction. The detailed modes of operation of these devices are complex and are not thoroughly understood, but in general they involve the formation of thin films at the junction of the surfaces, in which the molecules are so oriented or "polarized" that the transfer of electrons in one direction requires much less work than a similar transfer in the opposite direction. In some cases the conduction is metallic in nature, i.e., no decomposition of the conductor occurs (such as in the copper-oxide unit) whereas in other cases electrolytic conduction occurs, i.e., the conductor itself is decomposed by the passage of current and new chemical products appear at the electrodes (such as in the cupric sulphide unit).

Probably the oldest dry-contact rectifier is the humble crystal detector. Although this device can handle only very minute currents and voltages, its efficiency is high and its output wave-form good. Operating in much the same fashion, commercial devices are now available which will handle considerable power. Two main types are popular at present, the aluminum (or magnesium) copper sulphide valve, such as the Elkon and Benwood-Linze devices, and the copper-cuprous oxide valve, such as the Rectox and Kuprox units.

In the former, each element consists of a disc of cupric sulphide held in contact with a disc of magnesium-aluminum alloy under a pressure of about 200 pounds per square inch as shown at (A) of Fig. 150. Current can flow easily only from the cupric sulphide disc to the magnesium disc. In the copper oxide type shown in

(B), each element consists of a disc of copper oxide held in contact with one of copper. Lead washers between the brass terminal plates serve to produce uniform pressure over the entire surface of the copper oxide and copper discs. Current flows easily from the copper oxide to the copper, but not in the reverse direction

In general, contact rectifiers are simple in construction and have a high efficiency. All contact rectifiers, however, suffer from the fact that their characteristics vary with the condition of the contact surfaces and with the pressure upon these surfaces. In the cupric sulphide type of rectifier this fact is most noticeable, inasmuch as the rectifying junction is at the contact between two separate bodies of material. A change in pressure will change the area of contact between these dissimilar bodies and will also affect the nature of any absorbed gas film on the surfaces In the case of the copper oxide device, the rectifying action takes place in the interior of a disc, at the interface between the mother copper and the cuprous oxide formed chemically thereon. Thus a complete rectifying element is made up of only one physical body and the active junction that is formed during the manufacturing process is not altered subsequently by pressure, abrasion, corrosion or the like Pressure does affect the copper oxide rectifier, however, insofar as it determines the resistance of the contact made between the external conductor and the crystalline copper oxide surface Insufficient pressure will cause a high resistance joint between the rectifying element itself and the connection thereto, thus increasing the resistance in the current flow direction and decreasing output and efficiency The Kuprox unit is a riveted assembly and no adjustment of pressure can be made, but the other units are of bolted construction and their outputs can often be improved by tightening up the bolts and thus increasing the pressure on the elements.

Contact rectifiers resemble electrolytic rectifiers in possessing a definite breakdown voltage and breakdown temperature If either critical value be exceeded, the rectifier will pass current freely in both directions After the unit cools down, or after the high voltage is removed, it will immediately function again much as if it had never been overloaded. Rectox rectifiers have been broken down in this way ten times in succession without showing any permanent ill effects

Contact rectifiers, furthermore, all show leakage. Like the electrolytic rectifier, this leakage increases rapidly with temperature and to a certain extent with the age of the unit. For this reason it is extremely important that such devices be adequately ventilated; the unit itself should not operate appreciably above 90 100 F The leakage current in a Rectox full-wave unit charging a 6-volt storage battery will be 2 6 milliamperes at 70 F., 15-25 milliamperes at 90 F, and 60-100 milliamperes at 110 F A peculiar leakage phenomenon is demonstrated by some copper sulphide rectifiers which show markedly increasing leakage current in both directions If the rectifier output be short-circuited for a time, the threads will burn off, the leakage will be greatly reduced and the output and efficiency will be improved

Contact rectifiers have one other pecularity in common with electrolytic rectifiers, namely, that the completeness of rectification is affected strongly by current density or, what is similar, by the voltage applied to a given unit In the contact rectifier this does not come about as a result of capacity effects but rather because the ratio of "closed" and "open" resistances depends upon the voltage applied. This means that any given design of rectifier reqpires a certain minimum current to cause the rectifier to function properly. For a copper-oxide rectifier the minimum density is about 50 ma per square inch and the normal density 200-500 ma per square inch The Rectox rectifier unit has an efficiency of 60%. The breakdown voltage is about 11 volts a-c per disc and the critical temperature about 160° F. The life is probably the greatest of any commercial low-power rectifier and is measured in years. When higher voltages of alternating current are to be rectified or converted into pulsating direct current it is necessary to connect a number of units in series, as shown in the dry-plate rectifier unit at the right of Fig. 150. A suitable clamp or bolt supplies the pressure for the discs. The metal radiating discs serve to separate the various cells and to conduct away the excess heat.

The copper-oxide unit is claimed to have a rectifying ratio of 10,000 in one direction to 1 in the other, as compared to a 75-to-one ratio which is ascribed to the copper sulphide unit.

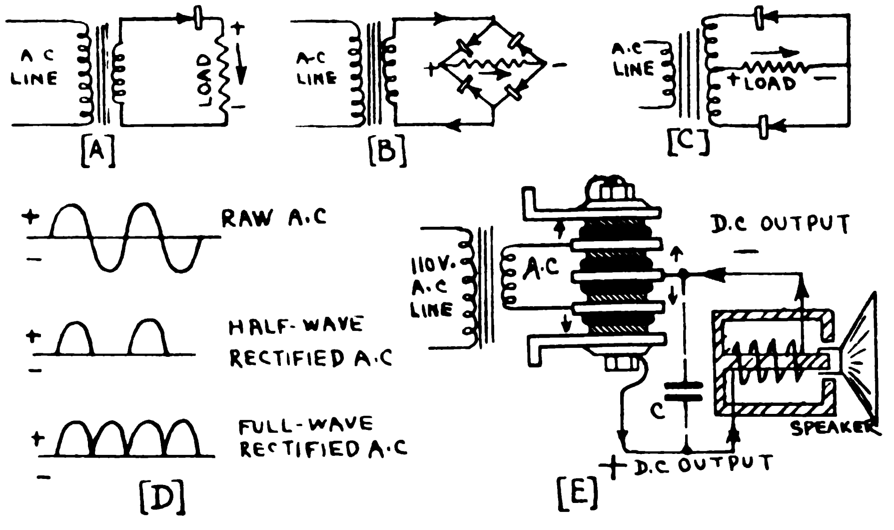
Connection of rectifiers for half-wave rectification: There are several different methods of connecting rectifiers, the choice of method being governed by the characteristics of the rectifier and the load.

The simplest form of rectifier circuit is the single-phase, or half-wave circuit

shown in (A) of Fig. 151. In this circuit, the rectifier is merely connected in series with the supply transformer and the load. The flow of current through the rectifier unit itself is in the direction indicated by the arrow-head which symbolizes the copper oxide (or the cupric sulphide) plate of one of the elements; the direction of the direct current through the load is shown by the arrow adjacent to the load resistance in the sketch. When the top of the transformer secondary is positive, current flows through the rectifier and load and back to the bottom of the winding. When the bottom is positive no current flows until the polarity of the transformer secondary again reverses. The load current is therefore a series of intermittent current pulses.

In this circuit the rectifier unit must carry the entire load current, and during the no-current part of each cycle it must withstand the peak voltage of the transformer plus the voltage across the load. Since current gets through the rectifier only during one alternation for each wave or cycle, this arrangement is called a *half-wave rectifier.* The rectified wave is shown at (D) of Fig. 151.

Connection for full-wave rectifier: If it is desired to have a more "smooth" output current than is produced by the above arrangement, or if better regulation of output



151—Various rectifier and circuit arrangements employed for half-wave and full-wave rectification of a-c current to pulsating d-c current A practical full-wave dry-plate rectifier arrangement designed to furnish the d-c current to the field magnet coil of an electro-dynamic type loud speaker is shown at (E).

voltage with load current is necessary, then two or more rectifiers may be connected so that both halves of the a-c wave are utilized, one rectifier filling in the gaps in the output of the other. One of the oldest of such full-wave circuits is the "Graetz Bridge" or "4-cell bridge" shown in (B). Here, four rectifiers are connected in series in a closed loop. Each half of the loop is made up of two units connected in the same direction, but the two halves of the loop are opposed to one another. The two junctions of unlike elements form the a-c input terminals, while the two junctions of like elements form the d-c output terminals. In the sketch, when the top of the transformer secondary is positive, the current flows through the upper left unit, through the load, and thence through the lower right unit to the bottom of the secondary Current is prevented from flowing in the opposite direction by the upper right-hand unit. When the polarity reverses and the bottom of the secondary becomes positive, the current flows through the lower left unit, through the load, and thence through the upper right unit back to the transformer. The output of such a rectifier will

resemble the output of two of the half-wave rectifiers described in the preceding paragraph, one being shifted a half cycle relative to the other as shown at (D). In this circuit any given unit carries only one-half of the total load current, although this current must pass through two units in series. In the closed valve position, one unit must withstand the peak transformer voltage plus half the load voltage. This arrangement is the one commonly used in full-wave rectifiers of this type employed in radio receivers. At (E) is shown the actual connections of such a rectifier arrangement designed to furnish d-c current to the field coil of an electro-dynamic type loudspeaker from the 110 volt a-c electric light lines. An electrolytic condenser C of from 12 to 2000 mfd. (low voltage dry type) is usually connected across the field to form a filter which effectively smooths out the ripples in the rectifier current.

Another full-wave connection is the bi-phase or "split-secondary" circuit shown in (C). In this common hookup, the transformer is wound for twice the desired voltage and a rectifier is placed in each leg of the transformer output, the two rectifiers facing in the same direction The load is connected between the center tap of the transformer secondary and the common connection of the two rectifiers In the sketch, when the top of the secondary is positive, no current can flow because the upper unit is closed However, the center of the secondary is also positive with respect to the bottom of the secondary, so current flows through the load, through the lower unit and back to the bottom of the transformer, only the lower half of the winding being active. Similarly, when the bottom of the secondary becomes positive it is rendered inactive by the lower unit, while the upper half becomes active, current flowing through the load and upper unit. Thus this connection achieves with two units the same output wave that was obtained by the circuit of "B" from four units, though with different conditions prevailing in the rectifier circuit. In this circuit each unit carries one half of the load current and that load current flows through only one unit at a time In the closed valve position, however, each unit must withstand the peak of the total transformer voltage plus the load voltage The total transformer voltage is twice the voltage which is useful at any given instant in the circuit. Since the peak voltage of one side of the transformer is nearly one and one-half times the "effective" or "r m.s." voltage, and since twice this voltage is applied to the unit plus the load voltage (which is generally nearly equal to the effective voltage of one side of the transformer), it follows that each rectifier unit must withstand approximately four times the output load voltage. This consideration is very important and limits the use of this circuit to rectifiers whose breakdown voltage is sufficiently high to permit safe operation under such conditions The thermionic tube and the mercury arc are in general best suited for use in this circuit

Having studied the action and connections of dry-plate rectifiers, we can now proceed with our study of the copper oxide rectifier type of electrical measuring instruments which have lately come into popular use. In these instruments, a small copper oxide rectifier is built into the instrument case and is employed to rectify the alternating current applied to the instrument. The resulting pulsating unidirectional current is sent to a sensitive moving-coil type of d-c milliammeter, (see Art. 196), as shown in the detailed connection diagram at (C) of Fig. 152. A simple full-wave copper oxide rectifier is employed. If *current* is to be measured with this arrangement, the terminals of the complete instrument are connected in series with one side of the line (the usual connection for ammeters), as shown at (A). If *voltage* is to be measured instead of current, the milliammeter used is of very low range and a multiplier resistor R, (see Arts. 202 and 204), is connected in series with the a-c terminals of the rectifier, as shown at (B). This type of meter is very useful since it can be used for measurements on both a-c and d-c circuits if suitable switching arrangements are provided for switching the rectifier in or out of the circuit at will.

A 3-inch diameter rectifier type a-c voltmeter with a range of 0-3

volts is shown at the right of Fig. 153. This has a resistance of 1000 ohms-per-volt. Notice its typical d-c movable-coil type movement.

Since the output of the rectifier is a pulsating direct current, as shown at the bottom of (D) of Fig. 151, the d-c meter will read the *average value* of the pulsating rectified current applied to it. A dry rectifier used in this service is so nearly ideal that the maximum and average values of the rectified current are the same as those of the a-c current. Therefore the meter will read the average value of the a-c current or voltage, which is equivalent to the effective value $\times$ .901. If a meter of this type is made up by the student, he should remember that the d-c meter reads 90% of the true alternating current flowing in the external circuit, and therefore he must multiply all readings by $\frac{1}{.901}$ or 1.11 to obtain the true effective value of the a-c. In meters sold commercially, the scale is already calibrated to read the true effective value of the a-c. Meters of this type are shown in Fig. 153.

Due to the fact that this constant proportionality exists between the reading of the d-c meter and the a-c input, the scale of the resultant

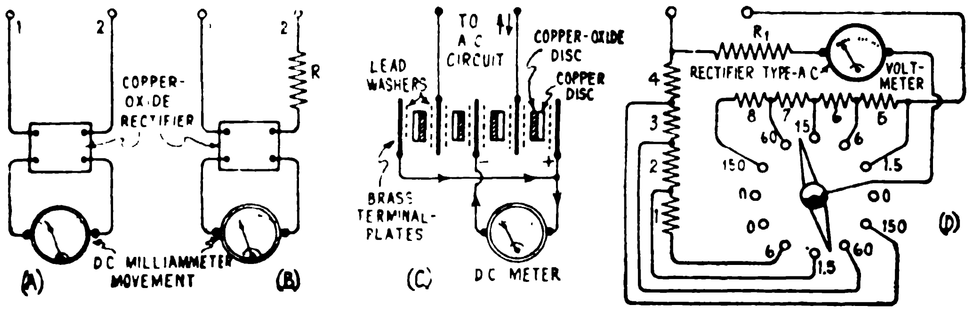


Fig 152 - (A) The connection of the rectifier unit to the d-c meter movement, in a rectifier type a-c milliammeter
(B) The connection of the rectifier, multiplier resistor, and d-c meter movement in a rectifier type a-c voltmeter
(C) The detailed connections of the parts of the full-wave rectifier unit to the d-c meter movement in a rectifier type instrument.
(D) Interior connections of all the parts of the copper oxide rectifier-type output meter shown at the left of Fig 153 The shunt and series resistors are so arranged that the overall impedance of the entire instrument is constant at 4000 ohms, for all ranges

meter is practically uniform rather than being of the inconvenient "square law" type (crowded at the lower end) found in other types of a-c meters.

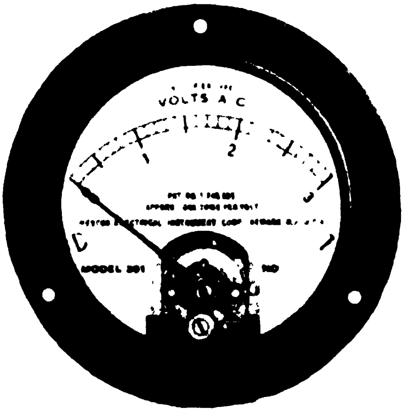
Up to 35,000 cycles per second the instrument indications of the usual type of copper oxide rectifier meter decrease at a substantially uniform rate of approximately ½ of 1 per cent for each 1000 cycle increase in frequency. For example, at 4000 cycles per second the instrument would indicate 4 $\times$ ½ = 2 per cent low. This correction may be applied when very accurate measurements are to be made.

Since the commercial rectifier instruments are calibrated with cur-

rents or voltages having a sinusoidal wave-form, the scale reads r.m.s. or effective values. It is obvious, therefore, that the instrument indicates correctly only if the currents or voltages measured have sine-wave shapes. For other wave-shapes, errors of varying magnitudes will result, the amount of error depends upon the variation from the true sine-wave shape.

A useful adaption of the rectifier instrument principle is shown at (D) of Fig. 152 and at the left of Fig. 153. This is a so-called "output meter" for measuring the signal output voltages of radio receivers and public-address amplifiers. The method of measurement is to feed the output of the set to a load resistance and measure the voltage drop produced across this resistor. The scale is calibrated in volts.

This complete instrument consists of a 5-range copper oxide rectifier type voltmeter enclosed in a Bakelite case Voltage ranges of 1.5, 6, 15, 60 and 150 volts are obtained by the dual selector switch. When one side connects more and more resistance (sections 1, 2, 3, 4) in *shunt* with the entire meter for the lower ranges, the other side automatically connects proper values of resistance (sections 5, 6, 7, 8) in *series* with the entire meter at the same time. These resistances are so proportioned



Courtesy Weston Elect Inst Co

Fig 153—Left: Copper oxide rectifier type output meter with 4000 ohm input impedance arranged for radio receiver testing

Right: Copper-oxide rectifier type 0-3 a-c voltmeter having a resistance of 1000 ohms-per-volt

that the instrument presents a constant non-inductive load of 4000 ohms to any circuit to which it may be connected, regardless of which voltage range is being used. It is arranged in this way, since the standard loud speaker or output transformer primary impedance which is across the radio receiver output during normal operation is also approximately 4,000 ohms. The power output in "milliwatts," of the receiver being

tested, can be calculated from the voltmeter readings and the known resistance (4000 ohms), since $W = \frac{E^2}{R}$.

This meter may also be used for the following purposes: To measure voltage output and compute power output of radio sets; to determine the maximum gain when lining up r-f and i-f stages of radio sets; to compare the gain of radio tubes; to determine gain when a calibrated input voltage is applied to a radio set or audio amplifier; to measure comparative selectivity of r-f tuners; to observe period and per cent of fading; to set or keep volume of sound amplifier equipment at an approximately constant value.

If it is desired to have the input impedance of the meter adjustable between certain limits, as is the case with an output meter used to test various radio equipment directly from the low impedance (10 to 100 ohm) windings of the loudspeaker output transformers, a tapped resistor or auto-transformer arrangement may be employed.

Note: For measuring the output of a radio receiver under test, an output meter may be connected directly in place of a magnetic (cone type) loud speaker, or of a dynamic speaker having a self-contained transformer. If, however, the instrument is to be substituted for the voice-coil of a dynamic speaker, it must be shunted by a resistance approximating that of the voice-coil. If the speaker is left in the circuit, the meter may be connected directly across the voice-coil or across the primary of the transformer (see Fig. 481A).

215. Resistance measurement by ammeter-voltmeter method: One of the simplest and most common methods of measuring resistances is by use of a d c. voltmeter and ammeter, or milliammeter, connected to a source of steady e.m.f. as shown at (B) of Fig. 154. The method consists in measuring the voltage drop produced across the device due to its resistance, when the measured current flows through it. Then from Ohm's law, we have: $R = \frac{E}{I}$.

Where R is the resistance in ohms; E is the voltmeter reading in volts and I is the current in amperes. A value of applied e.m.f. should be selected for the measurement such that the current flowing through the resistance of the device being measured will not overheat it.

When measuring very high resistances by this method, the current will be small and the voltmeter should always be connected across both the resistor and ammeter as shown at (A). If it is connected simply across the resistor only, as shown at (B), the milliammeter which must be employed to measure the current indicates the sum of the current through the resistor plus that through the voltmeter. Since the current through the resistor is small under these conditions, the voltmeter current may be almost as great (unless a high resistance voltmeter is used) and adding these together for the milliammeter reading causes an appreciable error. It is true

that at (A) the voltmeter measures the sum of the voltage drop across both the resistor and the milliammeter, but since the resistance of the average ammeter is only from 20 to 50 ohms adding this to the high resistance to be measured results in only a small error. For low resistances, the connection of (B) should be employed, for this case the current through the resistance will be comparitively large and adding a few milliamperes of voltmeter current to the ammeter reading does not cause appreciable error.

Example: Consider the circuit shown at (A) of Fig. 154. A voltmeter across the device whose resistance is unknown reads 100 volts and the ammeter reads 5 amperes. What is the unknown resistance?

Solution: $R = \frac{E}{I} = \frac{100}{5} = 20$ ohms. Ans.

216. Voltmeter method of measuring resistance: A simple method of measuring resistances by means of a voltmeter alone (whose exact resistance is known) is shown at (C) of Fig. 154. The proceedure is to measure the d-c supply voltage first with the voltmeter, by closing

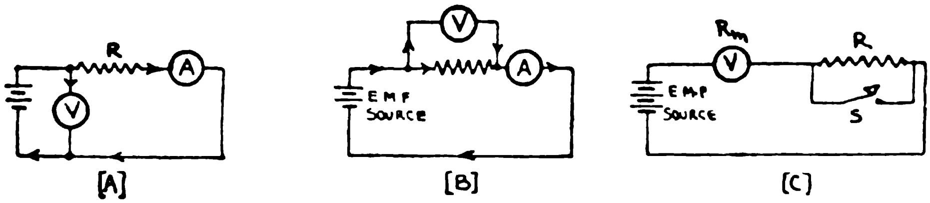


Fig. 154—(A) and (B) Methods of measuring resistance with an ammeter and voltmeter (C) Measuring high resistance with only a voltmeter of known resistance

the short-circuiting switch S which short-circuits the resistance to be measured. This is sometimes called the "line reading". Then the switch S is opened, thus putting the unknown resistor R in series with the voltmeter, and the reading of the meter is noted again. This is called the "drop reading". With these readings the value of the unknown resistor may be obtained from the formula.

$$R = \frac{E_L - E_D}{E_D} \times R_m, \text{ or } R = \left(\frac{E_L}{E_D} - 1\right) \times R_m$$

Where R=unknown resistance in ohms.

E_L=the voltage of the line or source, i.e., the voltage indicated by the meter when switch S is closed.

E_D=The "drop reading," i.e., the reading on the voltmeter when switch S is open and R is in series with the voltmeter.

R_m=the resistance of the voltmeter in ohms.

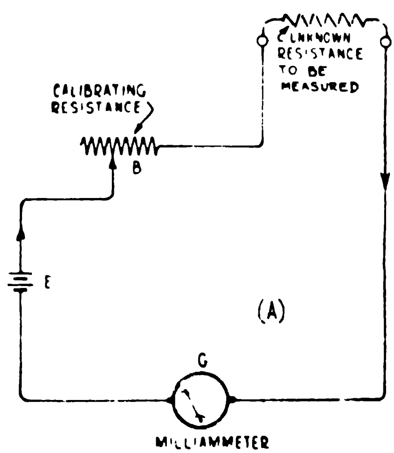
Example: **A 250 volt meter having a resistance of 1000 ohms per volt is to be used to measure the value of an unknown resistor. The voltmeter is connected directly across three B batteries in series and the potential is found to be 135 volts. The unknown resistor is then connected in series with the meter and the batteries and the meter now reads 35 volts. What is the value in ohms of the resistance.**

(Solution on next page)

Solution: Since the voltmeter has a resistance of 1000 ohms per volt, the total resistance, R_m, is 1000 times 250 or 250,000 ohms. E_L as measured is 135 volts. E_D is 35 volts. Therefore:

$$R = \left(\frac{135}{35} - 1\right) \times 250{,}000 = 715{,}000 \text{ ohms. Ans.}$$

Therefore, the only data needed to measure resistance by this method is the resistance of the voltmeter. This information may be marked on the meter or, if not, it can be obtained from the manufacturer. Weston models 301 and 280 meters each have a resistance of 62 ohms per volt, so that a meter having a range of 150 volts for instance, would have a re-



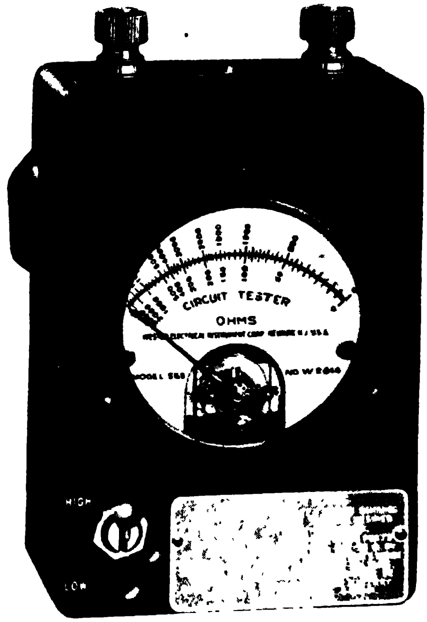


Fig 155—Left: Circuit of a simple ohmmeter

Right: A commercial type of ohmmeter used for testing coils, resistors, circuits, condensers, etc. It has two ranges 0-5,000 and 0-50,000 ohms. The switch at the lower left selects the range. The single dry cell is contained inside the case

Courtesy Weston Elect. Inst. Co.

sistance of $62 \times 150 = 9{,}300$ ohms etc. This method is only adapted to the measurement of high resistances, for if the unknown resistance is low there will be no noticeable difference in the voltmeter reading when it is connected directly across the e.m.f. supply line and when it is connected in series with the unknown resistor and therefore accurate readings cannot be taken.

217. Measuring resistance with the ohmmeter: An ohmmeter is an instrument that indicates the resistance of a circuit or device directly in ohms without need for any calculations. A commercial type of this instrument is shown at the right of Fig. 155. The device whose resistance is to be measured is connected directly across the ohmmeter terminals as in (A) of Fig. 155. The pointer indicates directly, the resistance of the device.

The principle of the ohmmeter is best understood by referring to (A) of Fig. 155. A dry cell E sends current through an adjustable calibrating resistor B, and a milliammeter G, the scale of which is marked directly in ohms. If the unknown resistor to be measured is connected directly across the terminals of the instrument, the meter deflection will be proportional to the current, but since the applied voltage is constant, the current depends upon the value of the unknown resistance. Therefore the deflection depends upon the value of the unknown resistance and the scale of the instrument may therefore be calibrated directly to read the value of the resistance in ohms.

As the dry cell voltage diminishes with age of the cell, the setting of resistance B must be varied. In practice this is accomplished as follows: The ohmmeter terminals are short-circuited by means of a short wire. Since the circuit resistance is now zero, the pointer should stand at zero. If it does not, resistor B is adjusted (usually by means of a slotted shaft) until the pointer stands at zero. When the pointer can no longer be brought back to the zero position by the means, the dry cell inside of the meter case should be replaced by a new one.

The ohmmeter shown at the right of Fig. 155 has two ranges obtained by using two separate series resistors which can be selected by the switch at the lower left-hand corner. One range covers from 0 to 5000 ohms and the other covers from 0 to 50,000 ohms. Ohmmeters can be used to find out if coil windings, circuits, resistors, or condensers are short-circuited or open, as well as for resistance measurements. If the device being tested has a short-circuit the ohmmeter reading will be "zero". If the circuit is open, or above the range of the meter the pointer will go off the scale.

Some meters of this type are made with several series multiplier resistors which can be put in series with the milliammeter movement to make a multi-range voltmeter out of it. Meters of this kind are called *Volt-ohmmeters*. One such instrument used extensively in radio circuit test work has ranges of 3, 30, 300 and 600 volts (all 1,000 ohms per volt) and two ohmmeter ranges, 0-10,000 and 0-100,000 ohms. Two toggle switches connect the various ranges of the meter in the circuit. The single dry cell flashlight-type battery for the ohmmeter is self-contained inside the meter case.

218. Measuring resistance—the Wheatstone bridge: The methods of resistance measurement described in Arts. 215, 216 and 217 are simple methods useful when no great precision is required. When resistance is to be measured accurately, some form of Wheatstone bridge is used.

The ordinary Wheatstone bridge consists of four resistors connected as shown, in the form of a diamond, with a resistor in each side of the diamond as shown at (A) of Fig. 156. Resistor X is the one whose value is unknown, and is to be measured; R is a resistor of known value; S and T are also known. A low voltage battery connected as shown to points A and C will cause current to flow in the resistors when the battery switch is closed. The current from the battery divides at A, one part flowing through path A B C, the other along path A D C., the two branches uniting at C and flowing back to the battery. Resistors S and T are so adjusted that when the galvanometer switch is closed, the galvanometer pointer stays at zero, indicating that no current is flowing through the galvanometer. This is called "balancing the bridge". Under these conditions the points B and D must be at the same electrical potential, for if any difference of potential existed between them it would send current

through the galvanometer circuit and a deflection would result, when the galvanometer key was closed.

Let I_1 be the current flowing through the path ABC and I_2 the current through ADC. By Ohm's Law, the voltage drop in any part of a circuit equals the current multiplied by the resistance of that part of the circuit. The voltage drop from A to B, therefore, equals I_1 X; that from B to C equals I_1 R; that from A to D equals I_2 S; that from D to C equals I_2 T. Now if points B and D are at the same electrical potential, the voltage drop from A to B must equal that from A to D or,

$$I_1 X = I_2 S$$

and also the voltage drop from B to C equals that from D to C, or

$$I_1 R = I_2 T$$

Dividing the first equation by the second, we have

$$\frac{I_1 X}{I_1 R} = \frac{I_2 S}{I_2 T}$$

Cancelling I_1 and I_2 we have, $\frac{X}{R} = \frac{S}{T}$ or $XT = RS$. From this we obtain, $X = \frac{RS}{T}$

This is the fundamental equation of the Wheatstone bridge. S and T are called the ratio arms of the bridge. The formula for the Wheatstone

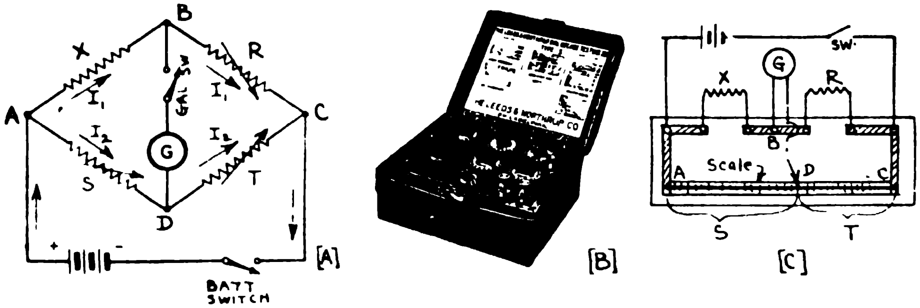


Fig 156 (A) Simple Wheatstone bridge circuit (B) Dial type bridge for field test work. (C) Simple slide wire form of Wheatstone bridge.

bridge may easily be remembered by remembering from XT=RS that *the products of the resistances of the opposite arms in the bridge are equal.* Thus, X times its opposite arm T is equal to R times its opposite arm S.

In actual practice it is not necessary to know the exact value of the resistances S and T as long as their ratio is known. With the ratio of S to T or T to S and the resistance of R known, it is a simple matter to determine the value of the resistance of X from the above formula. Notice that the formula contains the ratio of S to T. In practical Wheatstone bridges, the ratio arms, S and T are arranged so that the ratio between T and S can be varied progressively in multiples and sub-multiples of 10 while the variable standard resistor S is variable in small steps. A "decade resistance box" usually serves as the variable resistor R.

The accuracy of the determination of resistance X depends on the accuracy of the ratio arms S and T, the accuracy of the standard resistance S, the sensitivity of the galvanometer G and the relative resistances of all four arms of the bridge. Most accurate determinations are made

when all the arms of the bridge are equal, or at least approximately equal.

In practice the Wheatstone bridge is never constructed in the form of the diamond-shape of the diagrams. A much used form of the Wheatstone bridge is shown at (B) and (C) of Fig. 157. It consists of a number of different non-inductively wound coils of resistance wire each hav-

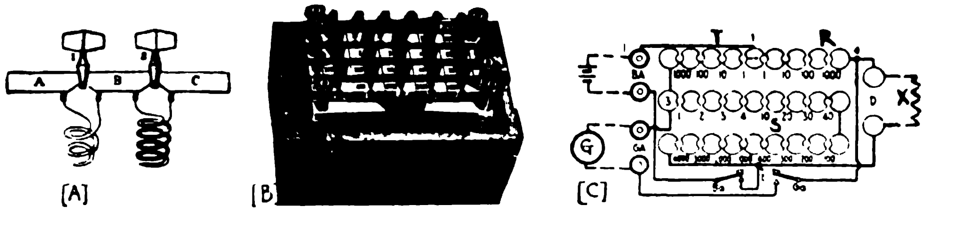


Fig 157—(A) Arrangement of non-inductive resistor coils and short-circuiting plugs (B) Post-office type Wheatstone bridge with coil plugs (C) Circuit of Post-office type bridge

ing a known marked resistance. The coils are connected to the short heavy brass bars on the top of the box. The individual bars may be connected by inserting round tapered brass plugs which can be easily removed. Each plug shorts the resistance coil connected between the two bars when it is put in place between the two bars, as shown at (A). Removing the plug puts the resistance coil into the circuit. The total resistance can be adjusted to any value by removing different plugs. This is sometimes called the *post office pattern* Wheatstone bridge. The complete bridge is shown at (B). In the Wheatstone bridge shown at (B) of Fig. 156, the resistances are varied by means of switches controlled by dials. These can be manipulated very easily and quickly. The galvanometer is built into the instrument.

Probably the simplest form of Wheatstone bridge is the *slide wire bridge* shown at (C) of Fig. 156. Point D is a sliding contact which is moved along the resistance wire A D C until a point is found for which there is no deflection of the milliammeter or galvanometer, G. The ratio S/T is then the ratio of the length of the two parts of the resistance wire. This is true because since the wire A C is uniform, the resistances of pieces of it are proportional to the lengths of the pieces. A rule or scale mounted under the side wire A C makes it easy to read off lengths S and T when the bridge is balanced. The same formula derived above is used for calculating the value of resistance X, only instead of using the resistance in ohms for S and T, the lengths of the slide wire are used instead. The slide wire bridge is very simple and inexpensive, and is capable of quite accurate measurements if care is taken in its construction and use. The resistance wire and resistors R and X are connected together by heavy solid brass rods as shown. This keeps the resistance of these connections purposely low, since any resistance in either of these connecting strips will be added to the corresponding resistance arms of the bridge.

A *dial* type Wheatstone bridge (B of Fig. 156) has the two ratio arms controlled by a single dial. Turning this dial corresponds to moving the siding contact in a slide wire bridge. Thus accurate and rapid work are possible with this form of bridge. The ratios in the usual form of dial bridge are 1:1, 1:10, 1:100, 1:1,000, 1,000:1, 100:1,10:1. The known resistor R is adjusted by means of four dials. If R is one ohm, X may be as small as .001 ohm. R may be as high as 1111 ohms and X may be 1000 times R. With this bridge any value of resistance from .001 to 1,110,000 ohms may be measured.

Problem: Referring to (C) of Fig. 156, R=10 ohms, S=40 centimeters and T=60 centimeters. What is the value of X?

Solution: $X=\frac{RS}{T}=\frac{10\times 40}{60}=6.67$ ohms. Ans.

The Wheatstone bridge can also be used for measuring inductances or capacitances as we shall now see.

219. Measuring inductance with a Wheatstone bridge: Inductance can be measured by means of a simple Wheatstone bridge arranged as shown at (A) of Fig. 158. This is usually called an *inductance bridge.*

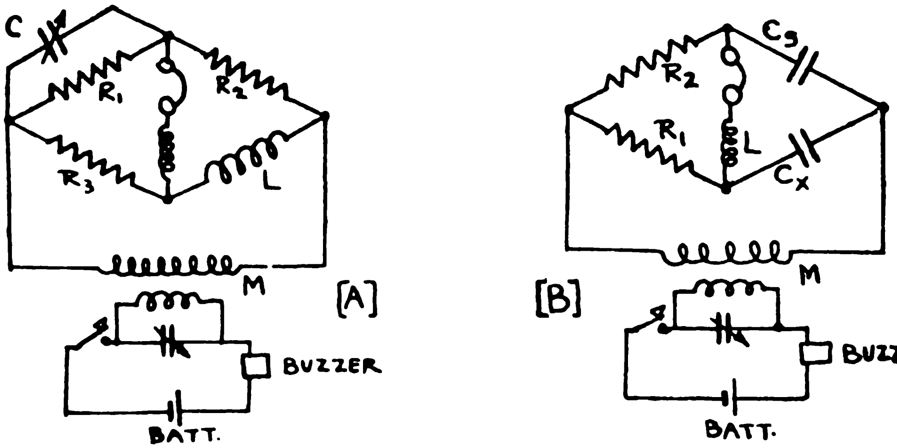


Fig 158—(A) Wheatstone bridge arrangement for measuring inductance
(B) Wheatstone bridge arrangement for measuring capacitance.

The four arms of the bridge consist of three resistance boxes, R_1, R_2 and R_3, and the inductor L to be measured.

The resistance of the inductor L, is first found by means of the Wheatstone bridge, using direct current. The bridge is now balanced for direct current resistance, and all three resistors and the inductor must be left as they are for the remainder of the test. The battery connected to the bridge is now replaced by a source of alternating current. Usually a 1000 cycle buzzer or oscillator is used for this purpose, for since the ear is most sensitive to frequencies around 1000 cycles, the point when minimum sound is heard in the earphones may be judged accurately. A buzzer is usually objectionable in that

its sound is heard for quite a distance and interferes with accurately determining the minimum sound point in the sensitive earphones. Coil M, couples the bridge to the buzzer or oscillator circuit. This may consist simply of two coils wound on a cardboard tube, or a telephone induction coil with its secondary in the bridge circuit. A variable condenser which has been calibrated is shunted across R_1 as shown. The small inductance coil shown is sometimes connected in series with the earphones to permit sharper adjustment for even the faintest sound. Sometimes a telephone transformer with a primary impedance of about 200,000 ohms and a secondary impedance of 20,000 ohms is connected here instead. The secondary is connected to the earphones. A grounded shield is used between the primary and secondary windings to prevent objectionable capacity effects. Now condenser C is varied until the sound is as faint as it is possible to get it. When this is done, the bridge is balanced for a-c. The resistance of L may be left out of the computations for it has been already been balanced out by the other three resistances. The junction of the two resistance arms should be connected to ground to prevent errors due to the capacitance between the earphones and the observer.

The four arms of the bridge, so far as a-c is concerned, are L, C, R_2 and R_3. L may be found from the equation:

$$\frac{L}{R_2} = \frac{R_3}{1/C}, \text{ or } L = CR_2 R_3$$

The quantity $1/C$ comes in due to the fact that if the resistance is increased the current is *reduced*, while, if the capacitance is increased the current is *increased*. Thus capacitance and resistance act oppositely so far as affecting the strength of the current is concerned. The resistances chosen for R_2 and R_3 must always be such that with the particular range of condenser employed the product $CR_2 R_3$ may be made numerically equal to the inductance L. For example, if C has a capacitance range from 0.00001 to 250 mfd., and R_2 and R_3 are 200 ohms each, the smallest inductance the bridge will measure accurately is about

$$L = .00001 \times 200 \times 200 = 0.4 \text{ microhenry.}$$

The resistors employed in the bridge must be of the non-inductive type and all wires should be kept as short as possible to prevent induction effects. Commercial forms of inductance bridges are used extensively in laboratories and in production work for checking the inductance values of coils of all kinds.

220. Measuring capacitance with a Wheatstone bridge: Capacitance may also be measured by means of a Wheatstone bridge as shown at (B) of Fig. 158. This is usually called a *capacity bridge*.

The four arms of the bridge consist of non-inductive resistors R_1 and R_2, an accurate standard condenser C_s, and the condenser C_x to be tested. Alternating current (1000 cycles preferable) is supplied to the bridge through the coil M, as in the case of Article 219. An earphone with a small inductance L, (or a telephone transformer as described in Art. 219) in series with it is used as a current detector. The resistances R_1 and R_2 are adjusted until the sound disappears or is as faint as possible.

The capacitance C_x is then found from the proportion

$$\frac{C_x}{C_s} = \frac{R_2}{R_1}$$

This is an inverse proportion, since if the resistance is increased the current is reduced, while if the capacitance is increased the current is also increased. The capacitance and resistance act oppositely in their

effect on the strength of the current. The junction of the resistors should be connected to ground for the same reason given in Art. 219.

If a variable condenser is being tested, the capacitance should be tested for a number of settings and a graph plotted with dial readings as abscissae (horizontal) and capacitance as ordinates (vertical).

The same precaution regarding short wires etc., which were set forth in Art. 219 must be observed in this test also. The room in which the test is made must be quiet, for noises will interfere with the accurate determination of the minimum sound point in the earphones. Commercial forms of capacity bridges are used extensively in laboratory and production work for quickly and accurately checking the capacitance of condensers.

221. Measuring frequency, the simple wavemeters: The property of frequency discrimination of a series resonant circuit may be used in an instrument for measuring the wavelength or frequency of the current in a circuit. If the instrument is calibrated in wavelength (in meters) it is called a *wavemeter.* If the instrument is calibrated in frequency (in cycles or in kilocycles), it is called a *frequency meter.* The construction and operation of the wavemeter and frequency meter are identically the same. The operation of the wavemeter depends on the principle of series resonance whereby the capacitive reactance is made equal to, and is neutralized by, the inductive reactance at the resonance frequency, and the impedance of the tuned circuit is then simply equal to its resistance. Under this condition the maximum current flows through the circuit (see articles 172 and 173). Therefore if a simple series tuned circuit is arranged as shown at (A) of Fig. 159, and is coupled either inductively or capacitively with the circuit M whose frequency or wavelength it is desired to measure, such that M induces a voltage of the same frequency into the tuned circuit, then the tuning condenser in the wavemeter may be adjusted until it is in resonance at the same frequency as that of M, and maximum current will be set up in the tuned circuit (Of course the inductance of the coil and the capacitance of the tuning condenser in the wavemeter must be so chosen as to give the range of wavelength or frequency required for the test.) At this condition of resonance, if L is in henries and C is in farads, the resonance frequency in cycles: $f = \dfrac{1}{2\pi\sqrt{L\,C}}$

If L is in the more convenient unit, microhenries and C is in microfarads, it is necessary to multiply the above fraction by 1,000,000. This gives finally: $f = \dfrac{159{,}000}{\sqrt{L\,C}}$

also the wavelength in meters will be: $\lambda = 1885\sqrt{L\,C}$ .... **(24)**

Example: A wavemeter has an inductance coil of 200 microhenries and is in resonance with another circuit when its tuning condenser is set at .0002 microfarads. What is the wavelength and the frequency of the tuned circuit?

Solution: $\text{Wavelength} = 1885\sqrt{LC} = 1885\sqrt{200 \times .0002} = 377$ meters..

$$\text{frequency} = \frac{159{,}000}{\sqrt{L\,C}} = \frac{159{,}000}{\sqrt{200 \times .0002}} = 795{,}000 \text{ cycles. Ans.}$$

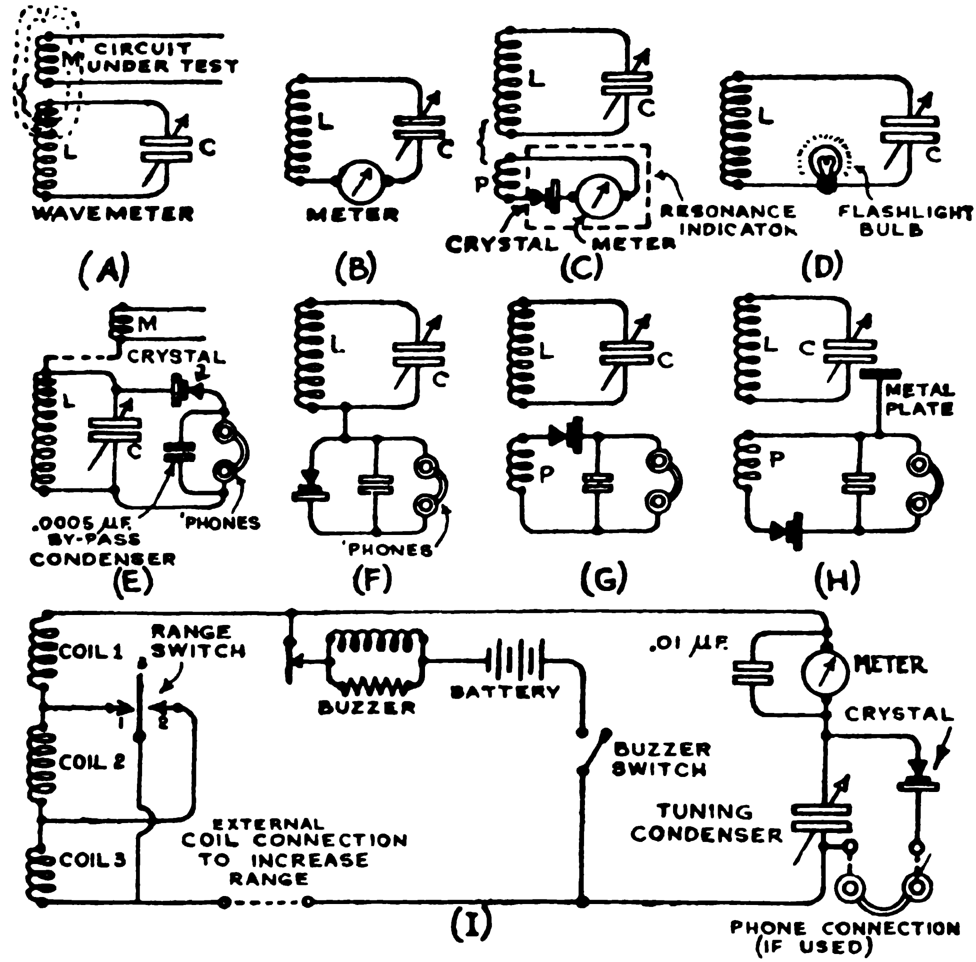


Fig. 159—Various wavemeter and frequency meter circuits. These enable one to measure the wavelength or the frequency of an a-c circuit.

Therefore if the value of the inductance and capacitance of the wavemeter at resonance are known, either the frequency or the wavelength can be calculated. In practical wavemeters, the tuning condenser scale is usually calibrated to read directly in frequency or wavelength.

In order to determine just when the tuned circuit of the wavemeter has been adjusted to resonance, it is necessary to have some device to indicate when maximum current is flowing through it. This is called the indicator. The indicator may be an a-c current meter, a small neon tube or flashlight lamp which will light up when maximum current is flowing in the tuned circuit, or a d-c milliammeter or pair of earphones with a crystal detector to rectify the current (this really forms a rectifier type meter). It may be connected directly in the tuned circuit as shown at (B), or, preferably coupled loosely to it by a coupling coil P consisting of a few turns of wire wound either around the main tuning coil or placed in inductive relation with it as shown at (C). The method at (C) is usually preferable to that at (B), because in the latter, the resistance of the indicating device is placed directly in the tuned circuit. This will tend to reduce the current flowing at resonance (since the current at resonance is equal to the voltage induced in the tuning coil, by the circuit under test, divided by the *total* resistance of the tuned circuit), and will also tend to broaden the tuning of the wavemeter (see (B) of Fig. 115). If the indicator is coupled loosely to the tuned circuit, its resistance will not appreciably broaden the tuning of the wavemeter.

The characteristics of the various resonance indicators which can be used, determine their selection for any particular case, depending on the use to which the wavemeter or frequency meter is to be put. In some cases, it is merely desired to have the indicator tell when the wavemeter is tuned to resonance with the circuit under test, in others it may also be desired to obtain a measurement of the strength or energy of the signal being tested, in which case a meter of some kind must be used to measure the current set up in the tuned circuit at resonance.

Where the power in the circuit being tested is considerable, as in the case of radio transmitter circuits, test oscillators, etc., the voltage induced in the wavemeter coil is comparatively large and the resonance indicator generally consists of a small flashlight bulb in series with the coil and condenser as shown at (D) of Fig. 159. At resonance the bulb burns brightest since the maximum current is flowing through it. A sensitive hot wire milliammeter (about 0 to 3 m. a.) may be used in place of the lamp bulb. In this case a .01 mfd. condenser should be shunted around its rather high resistance as shown at I of Fig. 159. Thermo-milliammeters are also used extensively for resonance indicators in these circuits. A small neon gas filled bulb connected across the tuning condenser may also be used as the resonance indicator.

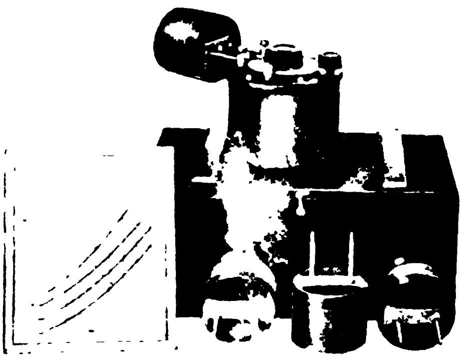
When the power in the tested circuit is very small, as in the case of radio receiver circuits, etc., a pair of earphones in series with a crystal detector rectifier may be shunted across the tuning condenser as shown at (E), or connected through a single wire as at (F). This makes a more sensitive resonance indicator since the earphones will respond to the slightest current through them. The arrangement at (E) depends for its action on the fact that at resonance the voltage across the terminals of either the tuning condenser or coil is at maximum and therefore the sound in the earphones is also maximum. When earphones are used, the current in the circuit under test must be modulated at an audio frequency in order to be heard in the earphones, since earphones will not respond to a steady high frequency current. Otherwise, modulation may be accomplished by a buzzer connected in the wavemeter circuit. The crystal detector rectifies the a-c current so that the earphones will operate. The wavemeter circuit is considered as being tuned exactly to resonance with the current in the circuit under test, when the sound in the earphones is at a maximum.

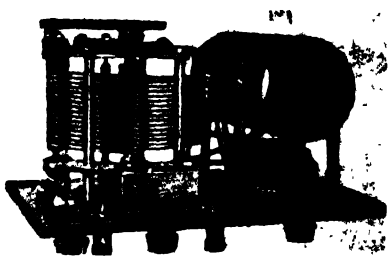
When the resonance indicator is placed in a separate circuit loosely coupled to the wavemeter circuit, as at (C) and (G) of Fig. 159, the energy in the indicating device is of course less than when it is directly in the tuned circuit as at (B). There are various ways of coupling the indicator circuit to the tuned circuit. A small coupling coil P, containing from 1 to 20 turns (depending on the amount of coupling desired) of magnet wire (about No. 18) wound on a 2 inch diameter bakelite tube may be placed

several inches from the tuning coil in the wavemeter as shown at (G); both usually being mounted in the same box. The coupling coil should not have too many turns or be placed too close to the wavemeter coil for then it will absorb so much energy from the tuned circuit, that the calibration of the wavemeter will be affected, and its tuning will be broadened. If the coupling coil has too few turns or is placed too far away, the indication of the resonance indicator will be too feeble. The coil should be so designed and placed that it gives the best reading for the purpose used, without causing any change in calibration of the tuning condenser. The fixed Carborundum type of crystal detector is probably the best type of rectifier for this type of circuit, since it need not be adjusted.

If the sound in the earphones is too weak, more energy may be introduced into the indicator circuit by a simple method devised at the Bureau of Standards. A metal plate or piece of tinfoil about 2x3 inches or 2 inches square is mounted near the stator plates of the tuning condenser and is connected to a point in the indicator circuit as shown at (H). This adds some capacitive coupling between the two circuits.

The coupling between the wavemeter and the circuit which is under test should always be made as loose as possible, that is, the meter coil should be kept as far from





Courtesy General Radio Co

Fig 160—Left: Simple wavemeter designed to tune from 15 to 220 meters by means of four plug-in coils shown

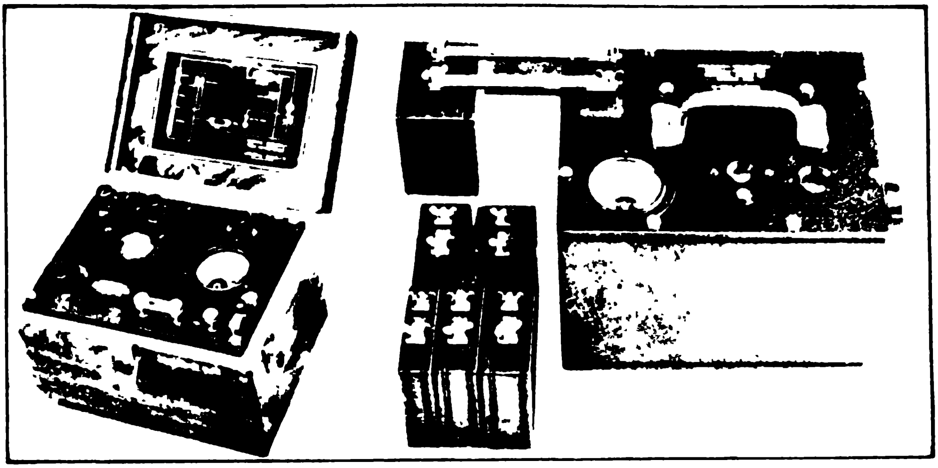
Right Inside view of self-contained wavemeter having range of 75 to 1500 meters by means of 3-section coil Resonance may be indicated by the hot-wire milliammeter or by earphones The circuit diagram of this instrument is shown at (I) of Fig 159 See also Fig 161

the circuit under test, as is consistent with a satisfactory reading of the indicator device. Coupling may be made as close as a few inches when very feeble currents exist in the circuit being tested, but with stronger currents the coupling may be several feet. With too close coupling, sharp indications of resonance cannot be obtained, since the close coupling broadens the resonance peak or may even make two distinct "peaks" or "maximum readings" separated considerably from each other This effect is really caused by the fact that even when the wavemeter current is tuned way off resonance and is therefore presenting quite a high impedance to the flow of current of the frequency under test, enough voltage is being induced in the wavemeter coil by the close coupling to the test circuit so that some current is forced through the wavemeter circuit anyway, resulting in a reading on the indicator. This will of course cause inaccurate measurements

In many cases, where it is impractical to inductively couple the circuit M *being tested*, to the coil in the wavemeter, on account of too distant separation, etc., coupling may be effectively accomplished by connecting a single wire from one end of the tuning coil in the wavemeter, to any point in the circuit under test, as shown at (E).

Wavemeters are usually built with the inductance fixed or semi-adjustable and the tuning capacitance variable, to enable them to be tuned to various frequencies within their range. All of the wires connecting the tuning coil and condenser must be heavy and as short and direct as

possible, so as not to introduce extra resistance into the tuned circuit. When a wide band of frequencies is to be covered, it is frequently necessary to use several coils of different inductance, which fit into the wavemeter by a plug-in arrangement, If the coils are arranged so one has exactly four times the inductance of the next smaller one, the wavelength range with any one coil will be approximately doubled and the frequency range approximately halved by using the next larger coil. If the coils are all built so the same winding space is used but with the number of



Courtesy General Radio Co

Fig 161—**Left.** Top view of direct reading wavemeter shown at the right of Fig 160 The wavelength in meters is read directly from the scale at the left The hot-wire milliammeter is at the right

Right: A precision wavemeter with plug-in coils, and a thermo-milliammeter resonance indicator Notice the heavy copper connecting straps from the removable coils, to keep the resistance of the tuned circuit low Additional coils are shown below

turns in this space double for each next larger coil, these conditions will be approximately closely. In wavemeters using several plug-in coils it is desirable to have the ranges of the coils overlap somewhat.

A simple wavemeter provided with a set of four plug-in coils fitted with mounting pins to fit the special tuning condenser terminals, and providing a total tuning range from 15-220 meters (20,000 to 1363 kc). is shown at the left of Fig. 160. This unit, having an accuracy of one per cent is very useful in many radio measurements and tests in the home or school laboratory. The tuning condenser with one of the coils inserted in place is shown on top of the wooden carrying box supplied with this wavemeter. A small flashlight bulb in a special socket which automatically closes the tuned circuit upon removal of the bulb, is provided. Any of the other types of resonance indicators may be connected to this wavemeter externally. The chart shown at the left supplies the calibration curves for the four ranges.

The illustration at the right of Fig. 160 shows the inside of a very useful self-contained direct reading wavemeter having a three-section tuning coil arranged with a switch for obtaining the wavelength ranges of 75 to 200 meters, 200 to 500 meters, and 500 to 1500 meters with the tuning condenser shown at its left. For the low range, the small front section of the coil winding is used alone. For the middle range the first two coil sections are in series. For the high range all three coil sections are in series. The range may be extended by connecting an additional inductor in series with this tuned circuit. The tuning condenser is provided with a reduction gear and vernier knob arrangement to enable its setting to be adjusted very accurately to the resonance point. The accuracy of this meter is one per cent. The hot-wire milliammeter mounted under the coil may be used for resonance indication, or a crystal detector (which is not visible in this photograph) may be used in conjunction with a pair of earphones for this purpose. The circuit diagram of this wavemeter is shown at (I) of Fig. 159. A top view of the instrument in its wooden case is shown at the left of Fig. 161.

A precision wavemeter employed for general laboratory and service uses where rapid and fairly accurate wavelength or frequency measurement is required, is shown at the right of Fig. 161. The plug-in coils are mounted in individual wooden cases for mechanical protection as shown. A thermo-galvanometer is used to indicate resonance. The accuracy of this instrument is 0.25 per cent and the wavelength range is 15-600 meters (20,000 to 500 k.c.). Another instrument of the same type is made, having a range of 70 — 24,000 meters (4,290 — 12.5 k.c.)

For very accurate measurements, a wavemeter should always be calibrated while using the same resonance indicator and wiring connections that are to be used whenever the meter is employed later. This applies to earphones, lamps, milliammeters, phone cords and all other similar parts. Any changes in these may change the inductance or capacitance of the tuned circuit and so affect the reading. For ordinary measurements this is not so essential.

Some wavemeters are equipped with buzzers to enable them to send out a modulated high frequency radio wave which can be picked up by a radio receiver or other device under test. The wavemeter at the right of Fig. 160, has a special high frequency buzzer mounted in the rectangular metal case directly in front of the tuning condenser. This is operated by an ordinary 4.5 volt C-battery mounted inside the wavemeter case.

Heterodyne wavemeters are probably the most useful type and are used extensively. In these, a tuned circuit, an oscillating vacuum tube and a milliammeter, (usually in the grid circuit of the tube), are employed; and very sharp indications of resonance are obtained by noticing when the sudden change in the milliammeter reading occurs. The wavemeter may also be used as an oscillator to produce high frequency current or waves.

When using a wavemeter, the setting of the tuning condenser is varied slowly until the particular resonance indicating device employed shows that maximum current is flowing in the tuned circuit of the wavemeter. Then the wavelength or frequency is calculated from the values of inductance and capacitance in the tuned circuit at the resonance setting by means of the formulas previously given, or else they may be read directly from the condenser scale if it is suitably calibrated.

REVIEW QUESTIONS

1. Name the three main effects which a flow of electric current can produce, and give two examples of the application of each in some practical electrical device with which you are familiar.
2. Explain the construction of the D'Arsonval type movement used in the Weston d-c electrical measuring instruments.
3. What causes the movable coil of instruments of this type to turn when current flows through it?
4. What is the purpose of the mirror that is mounted on the scale card of some instruments?
5. Since the mechanical construction and resistance of the movable coils of a Weston d-c voltmeter, ammeter and milliammeter are all the same, what then is the essential difference between these instruments?
6. How must a voltmeter always be connected to a circuit? (sketch)
7. How must an ammeter always be connected to a circuit? (sketch)
8. How is a wattmeter connected to a circuit? (sketch)
9. Draw a circuit diagram of a 6 volt storage battery connected to supply current to the filament of a vacuum tube in series with a 10 ohm rheostat. Indicate how you would connect an ammeter in the circuit to measure the current flowing. Also indicate how you would connect a voltmeter to read (a) the p. d. of the battery, (b) the voltage across the tube filament, (c) the voltage drop across the resistor.
10. What causes the Weston type of d-c measuring instruments to be "dead beat"?
11. A O-1 d-c milliammeter has a resistance of 30 ohms. Calculate the resistances of the shunts required to extend its range to (a) one ampere, (b) 10 amperes, (c) 50 amperes. What is the multiplying factor which must be applied to the meter scale readings in each case? Draw a diagram showing the connections of these shunts to the meter.
12. A voltmeter having a sensitivity of 1000 ohms per volt, has three scales, 7.5 volts, 150 volts, 450 volts. What is the value of the series multiplier resistance used for each range? Draw diagrams of the connections. How much current flowing through the movable coil is necessary to produce full scale deflection?

13. The range of the voltmeter of problem 12 is to be extended to 1000 volts. What multiplier resistance must be connected in series with the movable coil?
14. What is the essential requirement in a meter necessary to measure *e. m. f.* accurately and how is it fulfilled in the construction of a high resistance voltmeter?
15. What are the essential requirements of satisfactory meter multiplier resistors? How accurate need their resistance value be?
16. State the principle of operation of the hot-wire ammeter. Draw a sketch of a simple one and explain its operation. What are the advantages and disadvantages of this type of meter?
17. State the principle of the thermo-couple ammeter. What are its advantages?
18 Explain why hot wire ammeters or thermo-couple ammeters can be used either in a-c or d-c circuits.
19. Explain by a practical example, how a voltmeter having a comparatively low resistance may cause an appreciable change in the voltage of the circuit it is connected across. Show how the use of a high resistance voltmeter (1000 ohms or more per volt) eliminates this trouble.
20. Explain the operation and construction of a wattmeter and show why it can be used in a-c or in d-c circuits.
21. A power consumption test is made on a radio receiver by operating it and counting the number of revolutions of the aluminum disc in a recording watt-hour meter connected in the circuit. If the constant of the meter is 0 5 watts, and the disc makes 25 revolutions in 5 minutes how much does it cost to run the receiver per hour if electric power costs 8c per kilowatt hour?
22. Explain the construction and operation of the movable-iron type of a-c ammeter What are its advantages over the dynamometer type? Why can this type of meter be used either on a-c or d-c?
23. Explain the construction and operation of the rectifier type a-c. instruments? What are their advantages over the movable-iron or dynamometer types?
24. What is a rectifier? (Explain with aid of a diagram.)
25. Describe the action and construction of two types of dry-plate rectifiers.
26. Explain the principle of the Wheatstone bridge (with diagram).
27. What is meant by "balancing the bridge", and why is this done when measuring a resistance?
28. Referring to (A) of Fig. 156, resistor R is 10 ohms, S is 30 ohms, and T is 5 ohms when the bridge is balanced. What is the value of the unknown resistance?

29. Explain the principle of operation of a simple ohmmeter (with sketch). What is the advantage of the ohmmeter method of resistance measurement over that using a Wheatstone bridge? What are its limitations?
30. Explain how capacitance may be measured on a Wheatstone bridge.
31. Explain how inductance may be measured on a Wheatstone bridge.
32. What is the difference between a wavemeter and a frequency meter?
33. Explain the principle of operation of a simple wavemeter with a resonance indicator consisting of a crystal detector rectifier and a pair of earphones. Draw the complete circuit diagram the indicator circuit is inductively coupled to the tuning coil.
34. When a wavemeter is tuned to resonance with a particular circuit under test, the inductance is 300 microhenries and the capacitance is .0003 microfarads. What is the frequency of the circuit being tested? What is the wavelength?
35. Draw a diagram and explain how you would measure the value of a rather low resistance by means of an ammeter and voltmeter.
36. Draw a diagram and explain how you would measure a high resistance roughly by using a voltmeter alone.
37. A filament rheostat is the resistor in Prob. 35. The voltmeter reads 6 volts and the ammeter reads 0.5 amperes. Calculate the resistance.
38. A voltmeter having a resistance of 100,000 ohms gives a reading of 86.5 volts when connected in series with the secondary winding of an audio transformer across a source of voltage. When the voltmeter is connected across the line alone, it reads 110 volts. What is the approximate resistance of the winding? What would the first voltmeter reading be if the transformer winding were open at some point?
39. How does an ohmmeter indicate (a) a short-circuit in a condenser? (b) an open winding in a resistor or a transformer?
40. A frequency meter having a frequency range of 1500 to 500 k. c. (200 to 600 meters) is to be used in connection with a crystal detector rectifier and a 0-1 d-c milliammeter resonance indicator, to indicate when the frequency of a test oscillator reaches 400 kc. The inductance of the wavemeter coil is 300 microhenries and the maximum capacitance of its tuning condenser is approximately .00033 microfarads. What standard size of fixed condenser must be shunted across the wavemeter condenser to bring the range down to say 318 kc when the tuning condenser is set at maximum capacitance?

CHAPTER 14

ELECTROMAGNETIC RADIATIONS

SOUND AND ELECTROMAGNETIC RADIATIONS — STRUCTURE OF THE ATOM — HOW RADIATIONS ARE PRODUCED — FREQUENCY OF ELECTROMAGNETIC RADIATIONS — FAMILIAR RADIATIONS — EFFECTS PRODUCED BY THE COMMON ELECTROMAGNETIC RADIATIONS — HOW RADIO RADIATIONS ARE PRODUCED — THE BROADCASTING STATION — REVIEW QUESTIONS.

222. Sound and electromagnetic radiations: In Chapter 2, we studied some of the characteristics of sound waves produced by the mechanical vibration of air, and having frequencies between about 16 and 20,000 complete vibrations per second. In Chapter 2, it was mentioned that the broadcasting of sound programs could be accomplished practically by making use of electromagnetic and electrostatic waves or radiations of high frequency (commonly called radio waves), radiated in all directions over long distances from the transmitting aerial. Distant reception of radio programs almost daily proves that it is possible to hurl into space and scatter literally to the four corners of the earth at a speed of 186,000 miles per second, electric energy in the form of waves or radiations exactly representing the spoken words of the human voice or the music of great orchestras; and anywhere thousands of miles away on land or sea, or even in the air above, to pick out of the atmosphere a tiny bit of this energy and from it reconstruct the sounds almost as perfectly as they were originally produced.

We will now study some of the important characteristics of these radiations and will find that they belong to the same family as do those which produce the common sensations of heat and light. There are many fundamental things regarding the production and propagation of electromagnetic waves through space, which have never been explained to the complete satisfaction of scientists, and it is upon these questions that many of the most brilliant scientific minds in the world today are concentrating their efforts. Important data is being collected almost daily toward a solution of some of these entrancing mysteries of nature. The fact that we do not know as much about these things as we would like to, need not prevent us from making practical use of them, because there are many things with which we are on familiar terms in our daily lives, but which we really know little about. The origin of life itself is still a mystery.

223. Structure of the atom: We found from our study of the structure of the atoms of substances, in Articles 16 and 17, that all matter is composed of atoms, each one of which consists of a central nucleus of positive electrical charges (protons) and negative electrical charges (electrons), surrounded by one or more negative planetary electrons revolving about it in more or less circular orbits or shells.

Note: The student is advised to read Articles 16 and 17 carefully at this point in order to obtain a good mental picture of the atomic structure. He should study Fig. 17 especially.

It is imagined that in the more complicated atoms, planetary electrons are arranged around the nucleus somewhat as if they lay in a series of concentric shells or orbits. In the first shell are two planetary electrons (except in the case of hydrogen) revolving around the nucleus. In those atoms which contain more than two planetary electrons, all of the electrons in excess of these first two are arranged in shells external to the one just described as shown at (C) of Fig. 17, the capacities of successive outer shells for electrons being 2,8,8,18,18,32 and 32 respectively. Every one of the 92 chemical elements has a different electron arrangement. The total number of negative electrons revolving about the nucleus of each atom of any element (planetary electrons) is called its *atomic number*. There are of course, additional electrons inside the nucleus but these do not affect the ordinary electrical or chemical properties of the elements. The characteristic distribution of the electrons in any atom determines the properties of the atom.

In the following table, the total number of planetary electrons (atomic weight) and the number of electron orbits or shells in each atom is given for all of the 92 chemical elements. This table should prove helpful and instructive to the student in visualizing the structure of the atoms of the various chemical elements.

Chemical Symbols	*Elements*	*Number of Planetary Electrons*	*Quanta or Number of Electron Shells*
H	Hydrogen	1	1
He	Helium	2	1
Li	Lithium	3	2
Be	Beryllium	4	2
B	Boron	5	2
C	Carbon	6	2
N	Nitrogen	7	2
O	Oxygen	8	2
F	Fluorine	9	2
Ne	Neon	10	2
Na	Sodium	11	3
Mg	Magnesium	12	3
Al	Aluminum	13	3
Si	Silicon	14	3
P	Phosphorus	15	3
S	Sulphur	16	3
Cl	Chlorine	17	3
A	Argon	18	3
K	Potassium	19	4
Ca	Calcium	20	4
Sc	Scandium	21	4
Ti	Titanium	22	4
V	Vanadium	23	4
Cr	Chromium	24	4
Mn	Manganese	25	4
Fe	Iron	26	4
Co	Cobalt	27	4
Ni	Nickel	28	4
Cu	Copper	29	4
Zn	Zinc	30	4
Ga	Gallium	31	4
Ge	Germanium	32	4
As	Arsenic	33	4
Se	Selenium	34	4
Br	Bromine	35	4
Kr	Krypton	36	4
Rb	Rubidium	37	5
Sr	Strontium	38	5
Y	Yttrium	39	5
Zr	Zirconium	40	5
Cb	Columbium	41	5
Mo	Molybdenum	42	5
Ma	Masurium	43	5
Ru	Ruthenium	44	5
Rh	Rhodium	45	5
Pd	Palladium	46	5
Ag	Silver	47	5
Cd	Cadmium	48	5
In	Indium	49	5
Sn	Tin	50	5
Sb	Antimony	51	5
Te	Tellurium	52	5
I	Iodine	53	5
Xe	Xenon	54	5
Cs	Caesium	55	6
Ba	Barium	56	6
La	Lanthanum	57	6
Ce	Cerium*	58	6
Pr	Praseodymium*	59	6
Nd	Neodymium*	60	6
Il	Illinium*	61	6
Sm	Samarium*	62	6
Eu	Europium*	63	6
Gd	Gadolinium*	64	6
Tb	Terbium*	65	6
Dy	Dysprosium*	66	6
Ho	Holmium*	67	6
Er	Erbium*	68	6
Tm	Thulium*	69	6
Yb	Ytterbium*	70	6
Lu	Lutecium*	71	6
Hf	Hafnium	72	6
Ta	Tantalum	73	6
W	Tungsten	74	6
Re	Rhenium	75	6
Os	Osmium	76	6
Ir	Iridium	77	6
Pt	Platinum	78	6
Au	Gold	79	6
Hg	Mercury	80	6
Tl	Thallium	81	6
Pb	Lead	82	6
Bi	Bismuth	83	6
Po	Polonium	84	6
—	Alabamine†	85	6
Rn	Radon	86	6
—	Eka-caesium†	87	7
Ra	Radium	88	7
Ac	Actinium	89	7
Th	Thorium	90	7
Pa	Protoactinium	91	7
U	Uranium	92	7

*These elements are the Rare Earths †Tentative name-element recently discovered.

Notice that it is possible to tabulate the 92 elements in such a way that each one has one more planetary electron per atom than the element above it. This fact led to the discovery of many elements which were missing in this table several years ago, for it was known that the element with the electron structure enabling it to fit into the missing place existed somewhere. Some of the missing elements were found to exist in the atmosphere around the sun, etc. The search for and final separation of the missing element radium by Madame Curie, is a thrilling chapter in the history of science. Elements 85 and 87 have recently been discovered and named tentatively. Those listed beyond bismuth, exhibit radioactive properties similar to those of radium. Hydrogen with only one planetary electron is the simplest of all atoms, and uranium with 92 planetary electrons is the heaviest and most complex. It is one of the unstable radioactive substances, since changes are constantly taking place in its atoms with accompanying releases of tremendous energy per unit mass and change of chemical nature.

224. How radiations are produced: Normally, the planetary electrons are rotating around the nucleus of each atom in their proper imaginary orbits or shells and no external manifestations of energy are present. Each electron possesses a certain amount of potential energy depending on its distance from the nucleus. It requires the application of a force to move one of the electrons away from the atom, which would then contain an unbalanced positive charge. The actual potential energy becomes less as we pass from an outer shell to the one nearer the central positive nucleus. If, however, some external applied agency causes one of these electrons to be knocked or jarred out of its normal orbit or shell so that it is forced into one of the other shells an emission or absorption of energy takes place. If it is knocked from an outer to an inner orbit, the difference in energy corresponding to the two positions within the atom, must be given up in some other form This entire energy is radiated in the form of electromagnetic radiations and for each electron moved, a certain definite amount of energy known as one *quantum* is radiated into space and propagated at the uniform speed of 186,000 miles or 300,000,000 meters, per second. If an electron were to be removed from one shell to another farther away from the nucleus the potential energy of that electron would be increased and therefore work would have to be expended by the outside source to effect the transfer. Of course some applied agent may cause this to happen to countless numbers of atoms simultaneously in a body. Thus when electric current is sent through a gas such as neon, helium, etc., the gas becomes ionized due to a disturbance of the electron orbits of its atoms and when the atoms and electrons re-combine, electromagnetic energy is radiated at a frequency which produces the sensations of light on our optic nerve, so we say light is produced. This principle is used in the neon sign lights which are so popular today for advertising purposes. Energy is being absorbed from the source of electric current in the act of ionization, and radiated when recombination of the electrons and atoms occurs.

The converse of this action forms the basis of the operation of photo-electric cells used extensively in industrial devices, television and sound pictures. When an insulated, negatively charged metallic plate, is illuminated by light of suitable frequency or wavelength, it loses its charge because of a photo-electric emission of electrons. It is supposed that the electrons are knocked loose and emitted from the atoms of the metallic plate by the impact of the small quanta or bundles of energy which consti-

tute the electromagnetic light rays. A certain critical light frequency or color is necessary before the photo-electric emission takes place at all, depending on the material of the plate. For instance, for some metals, red light produces no emission while ultra-violet light is very effective. Only a few of the metals exhibit the photo-electric effect to any marked degree. In commercial photo-electric tubes or *cells* as they are called, various metals are used for the active surface depending upon the frequency or color of the light the cell is to be responsive to. For instance, zinc does not give off many electrons when exposed to ordinary light, but emits them quite freely when exposed to ultra-violet light. The commonly used metals for these cells are lithium, sodium, potassium, rubidium and caesium. The laws governing the photo-electric effect have been a strong argument in favor of the quantum theory of the corpuscular nature of electromagnetic radiations. (Photo-electric cells will be studied in Chap. 32.)

According to the Planck-Einstein theory of radiant energy, it is the scattering or radiating of these tiny units of radiant energy through space that constitutes the radio rays or waves that we commonly speak of. The exact nature of this radiant energy is not positively known as yet, nor is the exact way in which it travels through space known. We are not certain whether the energy is transmitted by a sort of wave-motion, as in the case of sound waves, or by tiny bundles of energy in a direct motion through space in straight lines like tiny bullets shot from a gun, and whether or not some material substance called the ether is necessary for their propagation through space. It is beyond the scope of this book to enter into an extended discussion of this subject, and even our most brilliant scientists have not yet reached definite conclusions on it. It seems probable at this time that the facts may best be explained by considering the wave theory to be an accurate representation of the facts when we have to deal with the operation of a large number of these bundles of energy (quanta), whereas in processes where an exchange of energy due to a single quantum is concerned, the quantum theory is necessary for a satisfactory explanation of the conditions.

Energy can be transmitted from one place to another by only one of two general means; either by a *wave disturbance* travelling through a medium which does not itself move as a whole (as illustrated by the case of sound waves in Figs. 2 and 3), or by the motion of corpuscles of matter from some source (as illustrated by the case of buckshot issuing from a shotgun), as shown in Fig. 162. According to the *wave theory*, an electromagnetic disturbance travels in the former way, by a wave motion through the ether. According to the *emission* or *corpuscular* theory, electromagnetic disturbances are propagated by invisible rapidly moving particles whose size varies with the frequency. As it is impossible for most minds to think of waves without a medium to carry the wave motion, it has been supposed that a hypothetical ether exists in all space, this ether serving as the medium to carry the wave motion. If the wave theory is upheld, then it must be assumed that at all points on a surface through which an electromagnetic wave is passing, energy is uniformly and continuously distributed. If the corpuscular theory is upheld, it must be assumed that the energy is distributed discontinuously in isolated bundles or quanta, being concentrated at points. At the present time, many facts do not find an adequate explanation in the simple wave theory and the quantum theory does not satisfactorily explain all observed phenomena associated with all types of electromagnetic waves. It seems probable that a combination of parts of the two theories will explain the observed facts more satisfactorily. The *wave mechanics* theory, which attempts to reconcile the conflicting views of these two theories, is rapidly gaining popularity. In this, it is assumed that in every mechanical system electrons are accompanied by waves. In this book we will speak of electrical and radio-waves and also of bundles of energy or quanta, when dealing with the propagation of electrical energy from the radio transmitting aerial to the receiving antenna.

The exact nature of the little bundles of energy is not yet positively known but it has been definitely established by a series of extremely delicate experiments performed by Professor R. A. Millikan, that a quantum shot off from an electron whose orbit lies close to the atomic nucleus is larger than a quantum that is radiated from an electron rotating in a larger orbit, further away from the nucleus. It is also known that the frequency of emission, that is, the number of groups or clouds of quanta shot off per second from electrons rotating in the inner orbits, is greater than the frequency of emission coming from electrons in the outer or larger orbits. The reason for this may be easily understood by remembering that the frequency depends entirely on how long it takes the electron

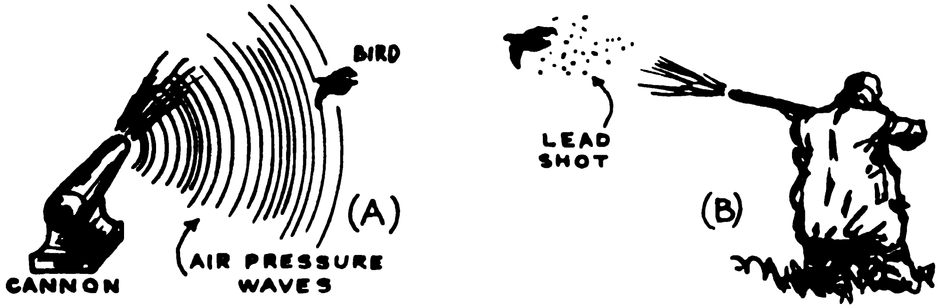


Fig. 162—(A) A bird may be killed at a distance by the concussion resulting from the explosion of a large cannon. The disturbance travels thru the air by wave motion from the region of the explosion. This illustrates rather crudely the propagation of energy by wave motion. (B) The bird may also be killed by being struck by lead shot from a shotgun. In this case the energy travels directly thru the air from the gun to the bird. This illustrates crudely the corpuscular theory of propagation of electromagnetic energy in tiny bundles

to travel back and forth over its path. The shorter the path of the electron, the sooner it completes a round trip and is ready to start over again, and the more closely the outgoing streams of energy follow the preceeding ones, i.e., the higher the frequency and the shorter the wavelength.

225. Frequency of electromagnetic radiations: Frequency, referred to alternating electric currents flowing in conductors, means the number of times the current or flow of electrons reverses in direction each second. Frequency as we apply it to radio, is simply the number of groups of these bundles of energy that are shot off into space from the radio transmitting aerial every second. It follows that the so-called *wavelength* is simply the number of meters that one group or cloud of quanta has travelled before the next one is started on its way. The energy is actually propagated through space at the speed of 186,000 miles or 300,000,000 meters per second. For example, if one million groups are shot off every second, the frequency will be one million, and each group will have travelled 300,000,000 $\div$ 1,000,000 or 300 meters before the next one is started. Therefore the *wavelength* is 300 meters. The greater carrying power of the shorter radio waves (high frequency) of 100 meters or

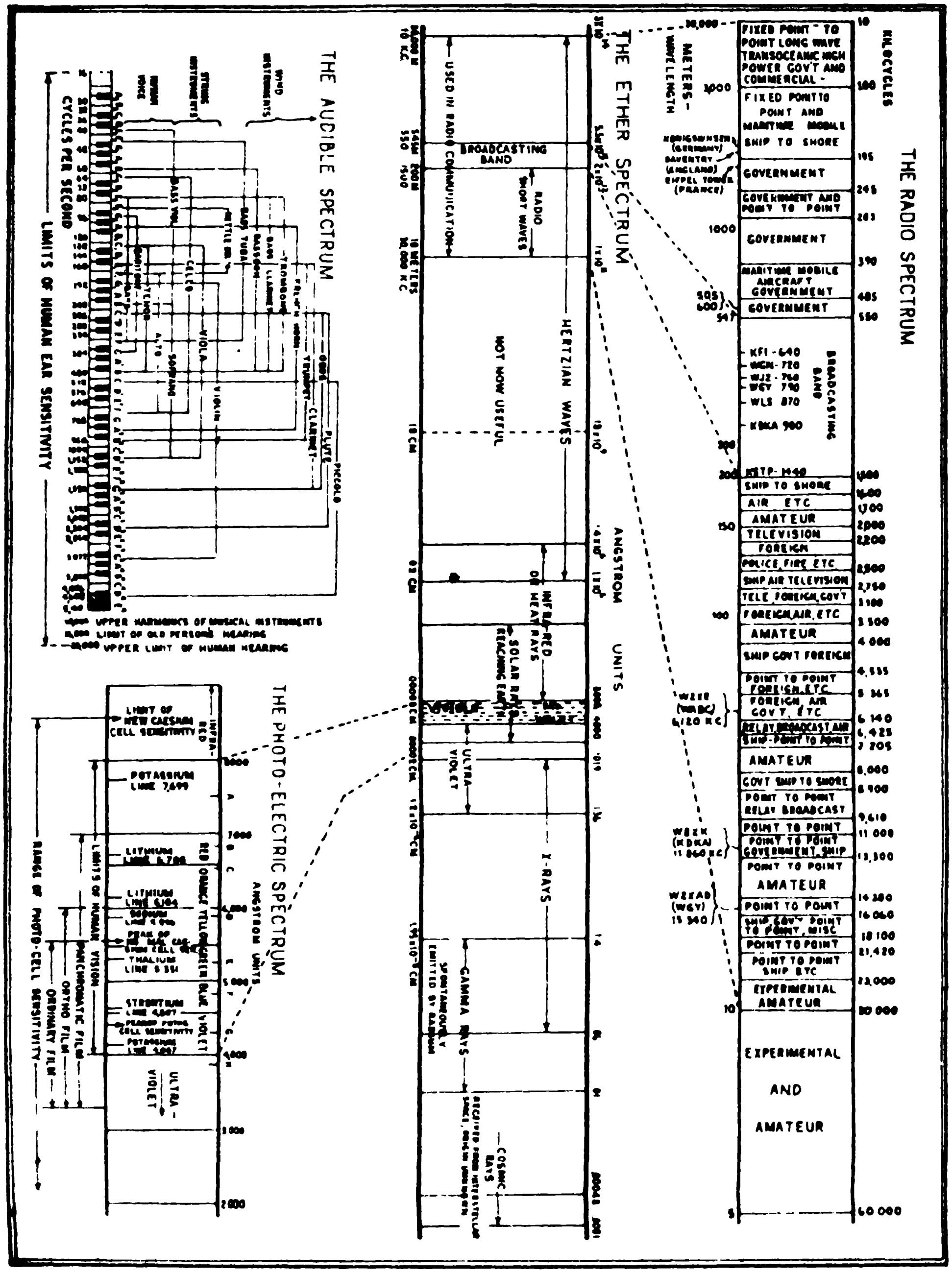
less may be explained by considering that the higher the frequency the larger is the size of the individual particles of quanta radiated from the transmitting aerial.

226. Familiar radiations: Radio waves or rays, radiant heat rays, visible light rays, ultra-violet light rays, X-rays, gamma rays emitted by radium, and the cosmic rays received from interstellar space, are all produced by similar electromagnetic radiations. The difference between them is that they are produced by radiations of different frequencies.

In the chart of Fig. 163 the spectrum of all electromagnetic radiations and the audible sound waves is arranged for convenient study. The ether spectrum chart shows the various electromagnetic radiations divided up into bands according to their frequency in k.c. and cycles, and their wavelength in Angstrom units (1 Angstrom unit$=$ 10^{-8} Cm.), meters and centimeters. The radiations having frequencies between 10 k.c. and about 60,000 k.c. constitute the so-called useful radio waves. This band is drawn to an enlarged scale at the top for convenience and labeled the *Radio Spectrum.* The small band from 550 to 1500 kilocycles is used for commercial radio and broadcasting, the transmitters of our common radio stations sending out into space electromagnetic radiations having frequencies lying within this band. The large band of higher frequencies between 1500 k.c. and about 60,000 k.c. is commonly termed the *short wave* band and is allotted for use by television broadcasting stations, amateur stations, etc., as noted. Radio amateurs are constantly pushing down into the shorter waves (high frequencies) and much experimental work is now being done on frequencies as high as 300,000 k.c. (1 meter wavelength). The short radio waves and radio heat waves discovered by E. H. Nichols and Dr. J. Tear comprise the range from about 3,000,000 cycles to 300,000,000,000 cycles per second.

Recently, radiations having frequencies between 10,000 and 14,000 k.c. (30 to 21 meters wavelength) were found to create artificial fevers in human beings by raising the temperature of the blood stream. These may prove helpful in studying the causes and cures for various fevers and other diseases. Above these lie the heat and infra-red rays, then come the visible light rays, arranged according to frequency as follows, (lowest frequency first) red, orange, yellow, green, blue, violet. This band from 8000 to 4000 Angstrom units is drawn to an enlarged scale at the lower left, and is labeled the Photo-electric Spectrum. Then comes the ultra-violet rays which are invisible and are sometimes referred to as "black light". These are given off by the sun, the electric arc, by X-ray tubes, etc. Above these is a gap which we know little about. Then come the X-rays, the gamma rays and the cosmic rays. The X-rays are produced in the X-ray tube by inpinging an electron stream travelling at speeds of the order of 100,000 miles per second on to a metallic target. Gamma rays are produced during the gradual disintegration of radium and by special recently developed forms of X-ray type tubes in which enormously high voltages are used to impinge an electron stream at very high velocity on to a metallic target.

Thus, all of the properties which we associate with the usual useful radio waves or rays, are produced by electromagnetic radiations having a frequency between 10 k.c. and 60,000 k.c. Radiations of higher frequency (shorter wavelength) produce manifestations peculiar to the shorter radio waves which are now beginning to be explored. For instance, during the ultra short wave transmission tests made across the English Channel on March 31, 1931, radiations having a wavelength of 18 cm. were employed. Since these lie in the frequency region near the infra-red and visible light rays (see Fig. 163) they behave similarly in some respects to heat and light rays, and ordinary reflectors were used at the transmitting and receiving stations for concentrating them, just as reflectors are used for concentrating heat or light rays. These so-called *quasi-optical* rays will be studied in Art. 570.



Courtesy Electronics Magazine.

Fig. 163—The complete spectrum of electromagnetic radiations. Electromagnetic radiations of different frequencies produce different effects as will be noted. Our eyes respond to only a small range of radiations (1 octave) as light. The audible spectrum of sound waves is at the upper left for comparison.

Little is yet known about cosmic rays of the type which are received from interstellar space, excepting that they are of extremely high frequencies and very penetrating. Only recently two Swiss scientists Professor Auguste Picard and Charles Kipfer made a most perilous flight to an altitude of 52,000 feet in a specially constructed baloon solely to collect data on the extremely high frequency penetrating cosmic rays radiated from interstellar space. Mr. G. Pendray writing in the Herald Tribune of May 31, 1931 says of these rays:

"Students of the cosmic rays, including their discoverer, Dr. Robert A. Millikan, of the California Institute of Technology, believe that they arise in space through the creation of matter from electrons or protons, or through the building up of heavy atoms from lighter ones in the hot centers of stars or nebulae. The cosmic rays are distinguished from all others by their extremely short wavelength and exceedingly great power of penetration. There appears to be no other way to account for their origin except by assuming that they come from the stars or from space, and that they represent tremendous changes taking place somewhere, involving enormous amounts of energy.

Some day, perhaps, when the true constitution and behavior of the atom and its components are thoroughly understood, a way will be devised to accomplish the complete transformation of matter into energy. The present studies, however, look rather toward obtaining a portion of the terrific energy that would probably be released if it were possible to create new atoms out of "free" protons and electrons, or more likely still, by the building up of relatively heavier atoms, such as those of helium, from atoms of hydrogen.

This is known as the development of power by "atomic transformation," as opposed to the present method of developing energy by "chemical reaction." When coal is burned, for instance, the heat is released through the chemical reactions of oxygen with carbon and other combustible material in the fuel. There is no change in the atoms of the materials concerned—only a change in the molecules.

The only example we now have of atomic transformation, is that found in the radioactive elements, such as uranium and radium. In them a genuine change in the atom takes place, with the release of tremendous quantities of energy. This energy, unfortunately, is in such form that its conversion into mechanical power is difficult—though probably not impossible. If some way were to be found to transform more common elements in the same way, releasing energy of somewhat similar nature, it is likely that part, at least, could be converted into heat.

Once that had been accomplished, the harnessing of the heat to do useful work would be relatively easy, and the energy thus secured, in proportion to the amount of substance utilized, would be tremendous beyond human experience. A cheap and simple method of atomic transformation, even though much of the resulting energy were lost in the process, might well solve the power problems of the world for all time."

227. Effects produced by the common electromagnetic radiations: From the foregoing it is evident that radio rays, heat rays, visible light rays, ultra violet light rays, X-rays, radium rays, and cosmic rays, are really all produced by electromagnetic radiations and may all be explained on exactly the same basis, see Fig. 164. They differ from the radio rays only in frequency. Gamma rays are produced by radiations within a band of frequencies almost 4 octaves wide (an octave of a frequency is a frequency twice as high); X-ray radiations cover a band 8 octaves wide, as do also ultra-violet radiations. X-rays have the peculiar property of passing through substances which are opaque to longer waves. They are not able to excite the optic nerve but if allowed to fall on certain fluorescent substances they cause these substances to emit radiations which do affect the eye and permit vision. Lead resists the passage of

X-rays through it. The ultra-violet light radiations also do not affect the human eye directly, but their presence can be detected by a photo-electric cell or by a photographic plate upon which they produce the same photographic effects that the ordinary visible light rays do.

Our eyes are really radio receivers tuned to respond to only a very narrow band of very high frequencies or short wavelengths; a band of about one octave (see Fig. 163). When the frequency of radiation is about 400 million-million cycles per seconds, we perceive the color *red* by means of the impression made on our optic nerve. When it is increased to 750 million-million cycles our eyes interpret the rays as *violet* light. All other colors are caused by various frequencies or combinations

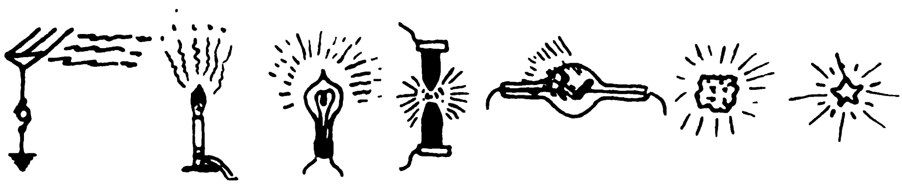


Fig 164—Radio, heat or infrared rays, visible light rays, ultraviolet rays, X-rays, radium rays, and the cosmic rays are all similar electromagnetic radiations of energy—differing only in the "frequency" of radiation

of frequencies lying within these two limits, as shown at the lower left of Fig. 163, outside of which our eyes cannot respond. Some grades of glass offer practically no opposition to light and little to heat. Metals offer little opposition to heat flow but are impervious to light.

The heat perception centers of our skin are also tiny radio receivers which are tuned to frequencies somewhat lower than those to which our eyes respond, and the physiological sensation we receive in that case is one of heat instead of color. The infra red or heat radiation frequencies lie within a band about 8 octaves wide. The production of electromagnetic radiations, of frequencies which affect our senses to produce the sensations of heat and light of different colors, may be illustrated by the following simple experiment.

Experiment: Heat a small piece of iron or steel (a hack-saw blade or a tenpenny nail will do) in a gas flame as shown at (A) of Fig. 165. It will first become warm and then hot, as you can prove by removing it from the flame every few seconds and placing your hand near it. Continuing the heating causes it to emit light and change color, first turning to a "dull red", then a bright "cherry red", to slightly "orange", and finally it gets "white hot". If the flame were hot enough to bring the temperature of the iron up to its melting point we would find it would give off a very bluish-white light just before melting.

What has taken place during this experiment? Applying heat to the iron caused its molecules and atoms to vibrate faster and faster as its temperature increased. This rapid vibration caused some electrons to jump to other orbits than their own, resulting in electromagnetic radiations within the particular band of frequencies which have the power of affecting our skin. Our nerves carried the effect to our brain,

where the intelligible impression of heat was formed. As the heating was continued the rate of vibration of frequency of the molecules increased, causing the radiations to follow one another more closely, i.e., the frequency increased. These higher frequency radiations produced the sensation of light in our optic nerve and became visible as red light. Continuing the heating, increased the frequency of vibration of the molecules and radiations, resulting in the production of orange, yellow and finally blue-white light as shown by the wave band representation at (B). If we could increase the frequency of these electromagnetic radiations still more by some means, we would produce violet light, ultra-violet light, X-rays, and finally gamma rays and the cosmic rays. All of these radiations, heat, light, X-rays, gamma rays, etc., are fundamentally the same. They are all electromagnetic radiations differing only in

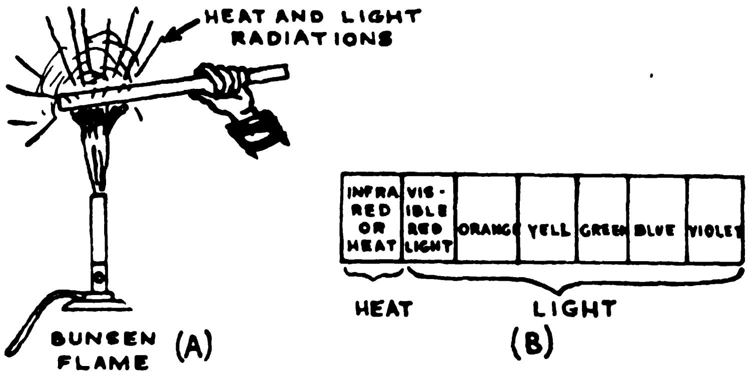


Fig 165—Producing heat and visible electromagnetic radiations by heating a piece of iron in a flame The spectrum of radiations produced is shown at (B).

frequency. Sound waves differ from these in that there is nothing electrical about a sound wave, it is simply a mechanical vibration, or actual to and fro motion of air particles.

228. How radio radiations are produced: There are many different methods by which atoms can be made to radiate at various frequencies, but we must confine ourselves now only to the one used for producing radio rays. In order to produce the frequencies used for radio transmission, which are very much lower than those necessary for light and heat, we must establish what might be called an artificial electron orbit, having a circumference infinitely larger than the largest natural orbit of the electrons found within an atom.

A coil of one or more turns of copper wire, or the aerial system of a radio transmitter, constitutes in effect, such an artificial orbit. If a stream of electrons, or in other words an electric current, is made to oscillate or flow back and forth in this circuit, radiation of quanta into space takes place at the same frequency as that of the electric current employed. If the frequency of the current lies between about 10 kc and 300,000 kc per second, the radiations produced will exhibit all of the properties which we associate with the so-called radio waves. One of the most important of these is that these radiations will travel over long distances through space without excessive dimunition in strength, so they may be used for the transmission of messages.

The frequencies found useful for radio transmission are far below those which our eyes or skin respond to directly, therefore we are compelled to construct artificial receiving instruments. When radio rays strike a receiving antenna or loop of metal they induce an e.m.f. in it and this causes a minute electric current to flow back and forth in the wire at the same frequency at which the energy has radiated. This minute electric current can be greatly strengthened by tuning the receiving circuits to electrical resonance at the frequency of the induced e.m.f. or current, and may be further amplified thousands or even millions of times and then converted into sound by the radio receiver.

Naturally, the actual amount of energy picked up by a receiving antenna is extremely small. It has been estimated that the amount of energy picked up by an average receiving antenna, coming from a broadcasting station 2,000 miles away, if made continuous day and night for thirty years, would about equal the energy expended by a common house fly in climbing up a wall a distance of one inch. The e.m.f. induced in an average receiving antenna by the radiations from a nearby broadcasting station of average power, is in the neighborhood of 50 microvolts (.00005 volts). Many modern radio receivers will produce a standard output of 50 milliwatts of power when as low as 5 microvolts is induced in the receiving antenna system of average dimensions connected to them (say 4 meters high and about 60 feet long).

This conception of the electromagnetic radiations employed in radio work, while still incomplete in many details, is probably far nearer to the actual facts than the older theory of a simple wave-motion in a hypothetical substance called the "ether of space," the actual existence of which has never been directly proved, while recent experiments seem strongly to indicate that it does not exist.

We do not know everything there is to know about radio-frequency radiations any more than we know everything about electricity, but just as with the case of electricity, we know how they behave under various conditions, and we are finding out more and more about how to control them for useful purposes. The question of how they travel, and what conditions affect them, is being investigated by many of our most brilliant scientific men, and it is safe to say that the time is not far off when we will know as much about the behavior of these radiations as we now know about simple electric currents, for they make modern radio broadcasting possible.

229. The broadcasting station: The electromagnetic radiations used in radio work are commonly produced by high-frequency alternating electric currents(called the "carrier current") flowing in suitably arranged circuits in the transmitting stations. These circuits will be studied later. The high-frequency currents (500,000 to 1,500,000 cycles per second used in ordinary broadcasting) are generated by large vacuum tubes known as."oscillators", since it is not practical to generate them with

the rotating type of electrical generators employed for generating ordinary 60 cycle a-c for electric light and power work. Each broadcasting station is assigned to *broadcast* or radiate energy at a definite frequency, by the government department in charge of licensing. Practically, all stations in the same vicinity at least, are assigned to broadcast on different frequencies or wavelengths, so that in any receiving station the principle of electrical resonance may be used to allow the reception and amplification of the signal energy of the particular station it is desired to receive and present such a high impedance to the flow of currents of all other frequencies (from other stations) that they are excluded from the circuits; and therefore the other stations are not heard at the same time. This is accomplished by "tuning" the receiver.

Thus, station W E A F in New York City transmits with a carrier current having a frequency of 660,000 cycles per second. The transmitting aerial of this station produces electromagnetic radiations of this frequency, which travel outward in all directions to the antennas of thousands of receiving stations located over a wide area. The wavelength of these radiations (and that of the station), is 300,000,000 divided by 660,000 or approximately 454 meters. Also, station W A B C located near it, transmits with a carrier current of 860,000 cycles, or a wavelength of 349 meters etc. Radio stations schedules and programs printed in newspapers usually give the frequency or wavelength of the station, or sometimes both. For convenience in tuning for stations, the tuning dials on some radio receivers are calibrated in kc and others are calibrated in wavelength. Many are simply calibrated with a scale divided into 100 equal parts, there being no direct relation between the scale divisions and either the wavelength or frequency.

If our eyes were capable of responding to the radiations sent out from the aerials of radio transmitters, these aerials would appear to us like so many huge lighthouses flashing on and off, each one a different number of times per second corresponding to the sound vibrations in the program being transmitted, and all radiating their energy out into space to be picked up by the receiving stations. Since each transmitter sends out radiations of different frequency, these beams would all appear as lights of different colors to our eyes. Such a sight would truly be fantastic and wonderful to behold. It would also enable us to understand more easily just how these radio rays travel from each broadcasting station to the many receiving stations.

REVIEW QUESTIONS

1. What is meant by wave motion? What forms of wave motions are you familiar with?
2. What is the essential difference between the wave theory of the propagation of electromagnetic energy and the corpuscular or quantum theory?

3. Explain by means of the latter, how electromagnetic radiations may be produced from a body.
4. What is the velocity of propagation of all electromagnetic radiations? What is the relation between the wavelength, frequency and velocity of these types of radiations?
5. A radio station broadcasts energy into the surrounding atmosphere, using in its aerial circuit a current having a frequency of 700 kilocycles. What is the wavelength of the radiations produced?
6. Does sound or light have the greater velocity? How could you prove your answer to be correct?
7. What difference exists between radio-frequency electromagnetic radiations and (a) heat rays; (b) ultra-violet rays; (c) X-rays; (d) the gamma rays from radium; (e) cosmic rays?
8. State some of the different properties of the various waves of problem 7.
9. A radio receiving set and the human eye both respond to electromagnetic radiations. Why then, do we not see the radiations being sent out by the radio broadcasting stations all around us?
10. What difference exists between those electromagnetic radiations which produce the sensation of *red* light and those which produce the sensation of *orange* light?

Chapter 15

RADIO TRANSMISSION, THE BROADCASTING STATION

THE PROBLEM OF RADIO-TELEPHONY — SIMPLE TRANSMISSION SYSTEM — PRACTICAL ASPECTS OF THE RADIATED ENERGY — TRANSMISSION SYSTEM WITH A GROUND — RADIATION RESISTANCE — THE MICROPHONE — ELEMENTARY RADIO TELEPHONE TRANSMITTER — MICROPHONE MODULATION — PERCENTAGE MODULATION — PRACTICAL TRANSMISSION — THE BROADCASTING STATION — ELECTRICAL TRANSCRIPTIONS — REMOTE CONTROL — ARTIFICIAL SOUND EFFECTS — CHAIN-STATION HOOKUPS — REVIEW QUESTIONS.

230. The problem of radio telephony: In Article 1 we mentioned that, in general the purpose of radio broadcasting or radio telephony is to transmit sound programs (speech or music) through the atmosphere to one or more receiving stations, without the use of connecting wires. The purpose of television broadcasting is to transmit visual scenes in more or less the same way. We also discussed the reasons why it was not practical to attempt to transmit the sound programs directly through the air, as in the case of one person speaking to another across a room. It was found that the problem could be solved satisfactorily by employing alternating currents of high frequency flowing in a suitable antenna system at the transmitting station. These currents produce electromagnetic and electrostatic fields (which we commonly call radio rays or waves) having the desirable property of radiating or spreading out into space in all directions over great distances without serious decrease in strength. Furthermore, it is possible by employing a suitable metallic electrical conductor (antenna wire) at any place through which these fields are travelling, to induce in this conductor electric potentials or voltages which can be strengthened or amplified. If the original sound waves in the transmitting station are made to affect the strength of the outgoing high-frequency currents and fields, then at the receiving station the received and amplified electrical impulses may be converted by suitable apparatus back into sound waves similar to those of the original sound program.

We are now ready to study just how these high-frequency currents may be employed to produce the radiated electric fields through space.

231. Simple transmission system: We have already mentioned that the high frequency alternating voltages or currents employed for radio transmission (frequencies employed in radio broadcasting are from 500,000 to 1,500,000 cycles per second) are most conveniently generated by vacuum tubes connected up as *oscillators*. The operation of these will be studied later. Let us consider the simple transmission system

shown at (A) of Fig. 166. Here a simple vertical antenna wire AB extends upward and a similar one AC extends downward to form a common *doublet* antenna. A generator G, of high-frequency voltage is connected at their junction. The two wires AB and AC have some capaci-

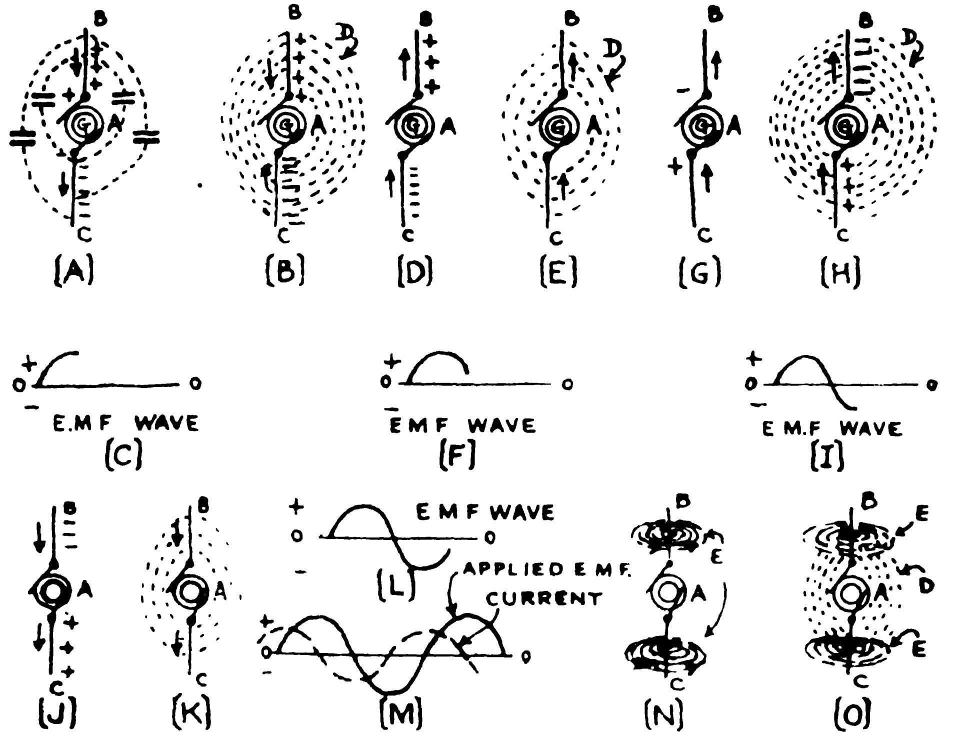


Fig 166—Electrostatic and electromagnetic fields existing around an antenna to which a high frequency a-c generator is connected

tance between them and since a difference of potential is maintained between them they may be considered to act as the plates of a condenser with the air between acting as the dielectric The detailed actions of such a system may be explained as follows:

Let us suppose the a-c alternator G is just starting on a positive cycle and charges wire AB positively and AC negatively, that is, electrons are transferred through the wire circuit in the direction shown by the arrows and are crowded into wire AC. This excess of electrons in AC causes electric forces to act on the atoms in the air dielectric between, and strains or distorts the electron orbits of the individual atoms exactly as in the case of the ordinary condenser studied in Fig. 83. These electric forces set up in the space around the antenna may be represented by imaginary *electrostatic lines of force* D extending from one wire to the other as shown at (B). The student should always remember that these lines of force are *imaginary*, and are merely brought into our discussions to enable us to show the directions and intensity of these electric forces in diagrams. These electric forces immediately start to spread out from the antenna wires in all directions at the velocity of light

(186,000 miles per sec.). In the meantime, the alternator voltage advances to the peak of the positive cycle as shown at (C), at which time the electrostatic lines of force reach a maximum value. While the e.m.f. has been rising, the flow of electrons through the wire (current) has been diminishing on account of the counter-charge built up by the crowding of the excess electrons into wire AC. As soon as the alternator voltage passes the maximum value and starts to decrease, as shown at (E) and (F), the excess electrons in wire AC immediately start to flow back into wire AB in the direction shown at (D), wire AC is becoming less and less negative and wire AB becomes less and less positive, so that the strain on the electron orbits in the air dielectric around the wire diminishes and they tend to assume their normal positions, and we say that the electrostatic field around the wire diminishes as shown at (E). When the applied e.m.f. reaches zero, the field will also be zero. Now the alternator starts on its negative cycle as shown at (I), charging the wire AB negatively and the wire AC positively, that is, electrons are forced through the wire circuit in the direction shown by the arrows at (H) from wire AC and crowded into wire AB. The electrons in the dielectric are now strained in a direction opposite to the previous case (see Fig. 83) and an electrostatic field of force is again set up in the region surrounding the antenna wires as shown at (H), but opposite in direction to what it was before. As the generator e.m.f. diminishes to zero again, as shown at (L), the electrons crowded into wire AB begin to flow back toward wire AC in the direction shown by the arrows in (K), the excess negative charge on AB diminishes and the strain on the electron orbits in the dielectric is also diminished again, so the electrostatic field is diminished as shown at (K).

We have now completed one cycle of the applied e.m.f. Let us see just what has happened around the antenna wire during this time. First we see that an electrostatic field was set up around it and died down during each half cycle, the direction on one half cycle being opposite to that during the next half. Also, during the cycle, a flow of electrons took place through the antenna wires AB and AC, first downward, then upward, then downward, etc. This constitutes a flow of electric current in just the opposite direction. If we draw curves of the applied e.m.f. and antenna current together on the same axis O-O as shown at (M), observing proper regard for the instantaneous directions of flow and strength, we see that the antenna current leads the applied e.m.f. by a quarter cycle. This is exactly what we should expect to find, since this is a condenser circuit. We also find that since current surges up and down in the antenna wires, a circular magnetic field will be produced around the wires at right angles to them in accordance with the principles of electromagnetism. This field may be represented by the circular imaginary lines of force E, at right angles to the electrostatic lines of force and to the antenna wires as shown at (N). At (O) both the electrostatic field D and the magnetic field E are shown in their true relative directions. In order to avoid confusion, the magnetic field is not shown on the previous diagrams. The electrostatic and electromagnetic fields just discussed, which are set up in the immediate vicinity of the antenna wire are called the *induction fields* to distinguish them from the *radiation fields* which play the important part in radio communication. The induction field corresponds exactly to the field around, or associated with, a wire carrying an alternating current in an ordinary electric light circuit, or the field in an ordinary transformer. The induction electrostatic field corresponds exactly to the electric field set up in the dielectric of any common condenser in an a-c circuit. Since the induction electrostatic field is in phase with the applied e.m.f., the induction electromagnetic field is always in phase with the electron or current flow producing it. and since the antenna current is one quarter cycle or 90 electrical degrees ahead of the applied e.m.f., it follows that the variations in the induction electromagnetic field always take place one quarter cycle ahead of those in the induction electrostatic field.

232. Practical aspects of the radiated energy: The *intensity* of the induction electromagnetic field diminishes as the *square* of the distance from the antenna, since it spreads out over a large area. This means that if its strength is a certain value at a distance of one foot from the antenna, the strength at 5 feet is one divided by 5 squared, or 1/25 as much. At 10 feet it is 1/100 as much, at 100 feet it is 1/10,000 as much. This means that the effects of the field rapidly weaken as the

distance from the antenna is increased. Therefore it plays practically no part in ordinary radio transmission, for at any considerable distance from the transmitter it does not exist at all.

Signals can be transmitted over relatively short distances by the induction field, using a-c of a frequency from about 300 to 3000 cycles. This is called "inductive signalling". One of its applications is in transmitting signals from a submerged cable to a ship almost directly over the cable, to aid the ship in navigating in darkness and fog through congested harbors.

Likewise, the induction electrostatic field around the antenna, diminishes in strength *directly* as the distance from the transmitting antenna is increased. Thus at two feet from the antenna the strength is one-half of that at one foot; at 1000 feet it is one one-thousandth of that at one foot etc. This assumes of course that there are no absorbing bodies in the path of the field. If the induction electrostatic and electromagnetic fields just described, diminish so rapidly in strength as we go away from the transmitting antenna and therefore do not take any important part in ordinary radio transmission over relatively long distances, what then makes it possible to receive our messages? The answer to this question is one of the things which our foremost scientists are now working hard to explain. We cannot see, feel or even measure these fields directly. We must measure them indirectly and must visualize them by means of the effects they produce.

If we accept the explanation offered many years ago, and still regarded as being substantially correct by many, we will believe that before all of the electrostatic field has had time to return to the antenna wire at (E), and (F), of Fig. 166, the alternator G, starts on its negative cycle, charging the wire AB negatively, thereby setting up a field that is opposite to what it was before, making it impossible for the remaining portion of the returning electrostatic field to give up its energy to the antenna. It is believed that this portion of the electrostatic field (called the *radiation* field) never returns to the antenna, but travels away from it with the velocity of light as a free wave, this action taking place during every half cycle of the alternator and continuing as long as the alternator voltage is applied to the antenna. It is assumed that this varying *radiation* field or electric force impresses in some way its variations or wave-form upon other vibrations, in the ether, which in turn, in some way transmit this wave-form with the speed of light through space, to be picked up by other electrical circuits, or antenna wires erected in its path.

If we think along the lines of the quantum theory explained in the previous chapter however, it would seem that when we apply alternating e.m.f.'s, of hundreds or thousands of volts and having the usual radio-frequencies of the order of say 600,000 cycles per second and higher, to the antenna circuit, the exceedingly rapid and intense straining action produced on the orbits of the planetary electrons of the atoms of the dielectric around the aerial wire, first in one direction and then in the opposite direction, as shown in Fig. 83, would cause many of them to be knocked from their normal orbits to orbits nearer the central nucleus of the atom. The difference in energy corresponding to the two positions in the atom would then be given up in some other form, this extra energy being *radiated* in the form of electromagnetic radiations or little bundles of energy. For each electron knocked into a new orbit a quantum of energy would be radiated into space and propagated at the uniform velocity of 186,000 miles per second. If we can visualize these tiny planetary electrons revolving about the nucleus in each atom, and can also visualize these almost inconceivably rapid electric forces tending to knock the electrons around first one way and then the next, thousands of times every second, it does not require a much greater stretch of imagination to see them moving in toward the nucleus of the atom where they will be attracted with a greater force by the nucleus and be better able to resist the outside forces acting on them.

While the author is naturally inclined to favor the explanation he has presented above in terms of the quantum theory, he wishes to caution the student against accepting either of these theories blindly at their face value. They have been given here in detail in an attempt to satisfy the natural curiosity of the student as to just how radio energy is produced and transmitted, to give some idea of what may be going on in the space around radio transmitting stations, and as an incentive for the student to do some original thinking on the subject for his own satisfaction and mental training. This entire new field of physics is stupendous in its possibilities and the student should try to reason these various actions out for himself to the best of his ability.

Leaving, for the time being, the question of exactly what the structure of the radiated field actually is and how it is propagated, let us study several of its important characteristics which are definitely known as a result of experiment.

First, no matter whether we assume that the energy is propagated in the form of electrostatic forces by a wave motion, or by quanta of energy radiated from the vicinity of the transmitting apparatus, it follows from our study of electric fields that the radiated electric field which is in motion will produce an associated magnetic field which is at right angles to it at every instant. Since this magnetic field is produced by the electrostatic field, any variations in it will be in phase with those of the electrostatic field. Thus the total radiation field really consists of a moving electrostatic field of electric forces and an accompanying inseparable magnetic field caused by its motion. These are not to be confused with the *induction* electrostatic and magnetic fields discussed previously, they are entirely different and separate. Their form will be shown later in connection with an antenna with an earth connection in place of the lower wire in the doublet here considered. It can be shown mathematically that the strength of the total radiation field falls off *directly* as the distance from the transmitter is increased. Thus, at a point a very short distance from the transmitting antenna, the intensity of the induction field may be stronger than that of the radiation field, but at greater distances, the induction field is exceedingly small compared with the radiation field, and its effect may be neglected so far as ordinary radio reception is concerned.

Neglecting any absorption of energy by the earth, by tall buildings with grounded steel frameworks, etc., the *total energy* in the radiated wave remains constant. Hence as the wave advances, the energy spreads out over an ever widening sphere with the transmitting antenna as a center, (assuming the antenna is not directional), and the *amplitude* of the variations in energy between the maximum and minimum during each cycle, decreases directly as the distance increases. The progressive decrease in amplitude of the radiated waves is somewhat analogous to the decrease in amplitude of water waves produced by throwing a stone in a body of water. As the wave disturbance spreads out in ever-widening circles, the amplitude of each succeeding wave and crest diminishes, since the original energy imparted to the water by the stone is spreading out over a larger and larger area. At great distances from the antenna the electric wave disturbance would be exactly perpendicular to the earth's surface if the earth were a perfect conductor. It is evident of course that the distance in meters (wavelength) travelled by the radiated electromagnetic disturbance during the time it takes the antenna e.m.f. or current to complete one cycle is equal to

$$\text{wavelength} = \frac{300{,}000{,}000}{\text{frequency}}$$

233. Transmission system with a ground: On ordinary broadcast band wavelengths, a doublet of the type considered in Fig. 166 suitable for radiating considerable amounts of power would have to be very long to be efficient, which means that the generating apparatus G, would have to be mounted very high. This, together with the cost of the high

supporting towers necessary to support the wires would be prohibitive. To overcome this difficulty, the lower half of the doublet is omitted and a connection to the earth is substituted for it, as shown at (A) of Fig. 167. The capacity effect then exists between the antenna and the earth, and the lower half of the electrostatic fields of Fig. 166 are missing altogether. In short wave transmission, where extremely high frequencies are employed, doublets are commonly used, for in that case the wire of the doublet

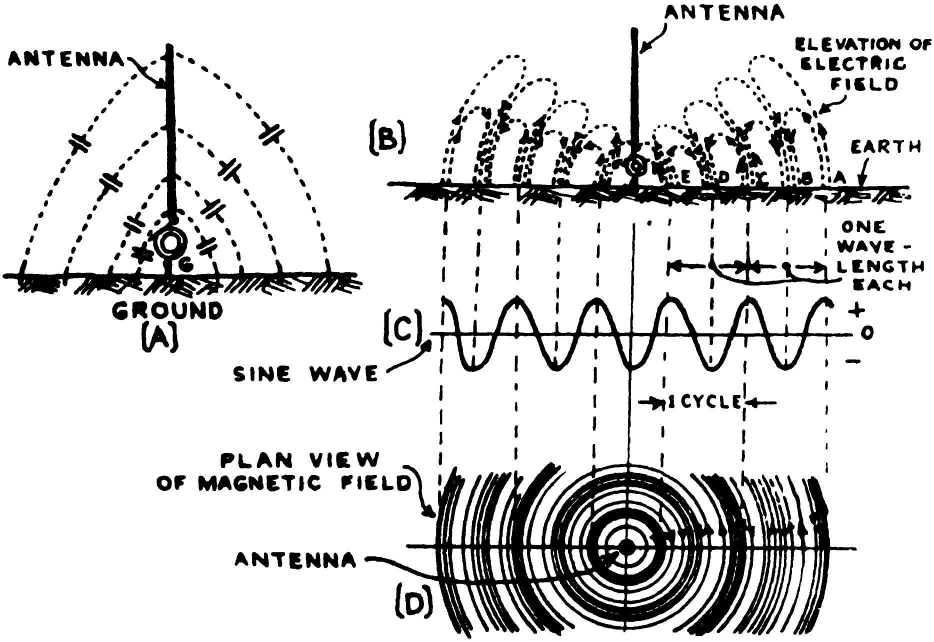


Fig. 167—(A) Condenser effect between antenna and ground. (B)-(D) Propagation of electric fields through space.

need only be a few meters long. It is usually possible to secure a much more efficient antenna arrangement with a doublet, since the resistance of the ground connection and that of the ground itself is eliminated.

The illustration at (B) of Fig. 167, represents what we would see if the radiated electrostatic field and associated electromagnetic were visible and we took a vertical cross-section view or slice right through the atmosphere in the plane of this paper. The illustration shows the fields which have radiated into the space around the antenna during the time it took to complete two and one-half cycles. At A the field is upward, and was produced by the current flowing say upward in the antenna wire just two and one-half cycles ago. During that time, this part of the field has moved out a distance equal to two and one-half wavelengths from the antenna as shown. At B the field is downward. This part of the field was produced by current flowing downward in the antenna wire two cycles ago. The upward field at C was produced by current flowing upward one cycle ago, etc. The radiated magnetic field is at right angles to this electrostatic field and since it would be perpendicular to the plane of the paper, part of it is shown in plan view at (D). The circular magnetic lines of force are shown as they would appear if we looked directly down on the transmitter from a balloon or aeroplane. Notice the comparative directions of the magnetic field

and the corresponding electrostatic field at (B) at any instant. The wave-form corresponding to both is shown at (C). At the "maximum" points in each direction, the fields are maximum in strength; at the "zero" points, the fields are zero. If the generator (G) were applying a sine-wave e.m.f. to the antenna circuit, these radiated fields will follow one another in succession, each one being exactly like the next.

The two radiated fields move outward from the antenna, at all times perpendicular to each other, the magnetic field being parallel to the ground and the electrostatic field being perpendicular to it. At the same time, both fields are at right angles to the direction of propagation. At great distances from the antenna, the electrostatic field would be exactly perpendicular to the earth, if the earth were a perfect conductor. Actually the resistance of the earth's surface causes the field to tip forward somewhat, as shown at (B).

Possibly the following description by Dr. Fleming will serve to make the actions taking place during the propagation of these fields clear:

"If we can imagine a being endowed with a kind of vision enabling him to see the lines of electric strain and magnetic flux in space, he, standing at any spot on the earth's surface, would see, when the antenna was in action, bunches or groups of electric strain fly past. Near the earth's surface these strain lines would be vertical. Alternate groups of lines of strain would be oppositely directed, and the spectator would also see groups of magnetic flux fly past, directed in a horizontal direction or parallel to the earth's surface. The strain and flux lines would move with the velocity of light, 186,000 miles per second, or 300.000,000 meters per second, and the distance between two successive maxima of electric strain, directed in the same direction, would be the wavelength of the wave."

The higher the frequency of the applied e.m.f., the more the energy being radiated, the radiated energy being proportional to the *square* of the frequency. This shows why it is necessary to use high frequencies to get a radiation field sufficiently strong to allow successful communication with a medium amount of power employed. With the ordinary type of elevated antenna, the radiation field at a given point due to an alternating current having a frequency of 500,000 cycles (wavelength of 600 meters) would be 25,000,000 times as strong as that produced by an equal current having a frequency of 100 cycles. This is the reason why high frequencies, or "radio frequencies", are used for the carrier wave in radio transmission and why it is possible for the signals of amateur stations transmitting at frequencies above 6,000,000 cycles per second (below 50 meters) to reach nearly around the world, employing powers of but a few watts.

234. Radiation resistance: An antenna of the common type discussed here really forms a condenser. If the antenna were replaced by an air-dielectric condenser having no losses, and having a capacitance equal to that of the antenna, and the circuit were tuned to resonance by an antenna series inductance, it would be found that the current in this circuit is much larger than that obtained at the base of the antenna with the same power input, when the actual antenna itself is used instead of the condenser.

If a non-inductive resistance were now added to the condenser circuit and its resistance adjusted until the antenna current was the same(for the same power input) as before, this value of resistance is called the total *antenna resistance*. The added resistance consumes energy at the same rate as the antenna, and therefore the total effective resistance of the antenna must be equivalent to this resistance added to the antenna circuit. The power consumed in either case is equal to I^2R, in which I is the current and R is the resistance. Hence the total antenna resistance may be defined as the effective resistance that is numerically equal to the quotient of the average power in the entire antenna circuit divided by the square of the effective current at the point of maximum current.

Of this total energy, part only is radiated away, the remainder being converted into heat in the aerial circuit. Now the effective resistance R may be looked upon as consisting of two separate component resistances, one acoounting for the losses in the aerial circuit including radio-frequency resistance of the conductors, ground resistance, insulator leakage, dielectric losses, etc., and the other accounting for the useful power radiated. This latter fictitious resistance is called the *radiation resistance* of the antenna; it is that equivalent resistance which, when multiplied by the square of the antenna current, gives the useful power being radiated. The radiation resistance is used as a measure of the ability of an antenna to radiate power. An antenna with a high radiation resistance is a good radiator and vice versa.

It can be shown that the radiation resistance is proportional to the square of the *effective height* of the aerial, and to the square of the frequency or inversely proportional to the square of the wavelength. The effective height is not equal to the actual height of the horizontal portion above the ground because the earth is not a perfect conductor and trees, etc., influence radiation, and also because the vertical portion possesses capacity. Still, the effective height is roughly proportional to the actual elevation.

235. The microphone: In order to broadcast sound programs by radio we must first convert the to-and-fro vibrations of the air which constitute the sound waves, into corresponding variations of current in an electric circuit. The device for accomplishing this is known as the *microphone*. There are several types of microphones in use in radio telephony and in sound picture work, but perhaps the simplest one for us to understand at this time is the popular carbon type. The others will be studied in Art. 549. The principle of operation of the carbon microphone used in radio is exactly the same as that of the common telephone transmitter used in millions of homes. The microphones used for radio broadcasting are designed to operate satisfactorily over a wide frequency range which includes both that of speech and that of musical frequencies up to around 5,000 cycles. The ordinary house telephone transmitter is designed to operate only over the limited range of important speech frequencies from about 250 to 2700 cycles.

The method by which the carbon microphone changes the air pressure variations of sound waves into corresponding variations in current in an electric circuit, is really very simple, as we shall now see.

At (A) of Fig. 168 we have a "single button" microphone of the simplest kind connected in series with a dry cell, or other source of low-voltage of constant e.m.f. In this circuit may also be placed a d-c milliammeter having a range from 0 to 50

milliamperes. The light diaphragm A, of thin flexible duraluminum, is rigidly fastened to the polished carbon button B, and is held more or less fixed around its outside edge by the insulated housing E. A second carbon button D, is fastened in place at the back as shown, and the space between is filled with tiny loosely packed carbon granules C, about the size of fine granulated sugar. An electrical connection is made to each of the carbon buttons, so when the microphone is connected in an electrical circuit as shown, current must flow from one button through the carbon granules to the other one. The carbon granules make imperfect electrical contact with each other so they offer quite some resistance to the flow of current through them. In the common type of broadcast microphone, this resistance is normally about 100 ohms-per-button. Therefore, a small steady current $I = \frac{E}{R}$ will normally flow through the

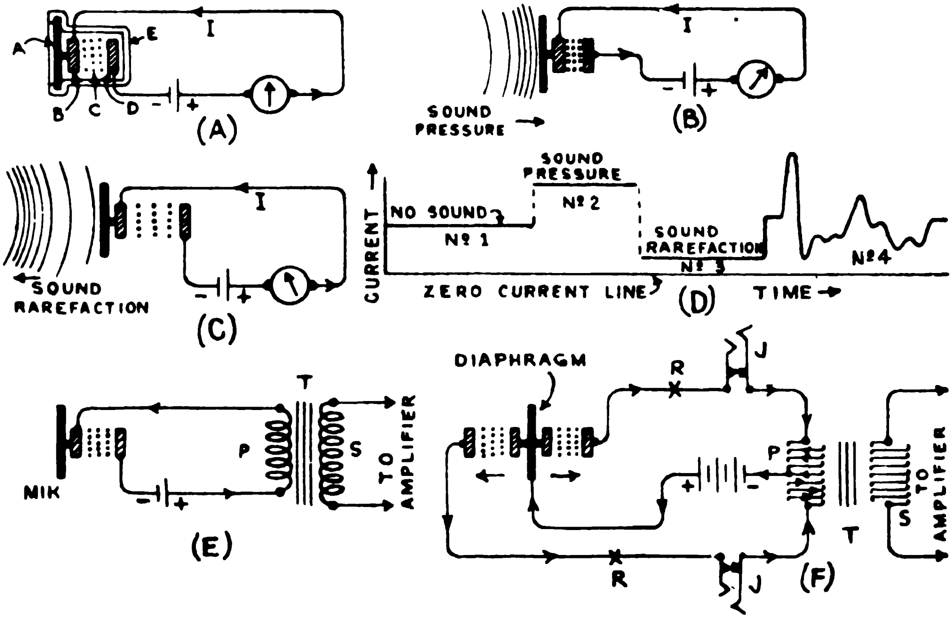


Fig 168—Action of the single and double-button carbon microphones.

microphone circuit, where E is the applied voltage and R is the total resistance of the microphone and the rest of the circuit. This current will be indicated by the milliammeter in the circuit and is represented by No. 1 at the left of (D). Let us imagine now that someone speaks into the microphone. The sound waves which really consist of a series of alternate pressures and rarefactions in the air (see Fig. 3) will act against the diaphragm A and cause it to vibrate back and forth slightly in accordance with these pressures. For instance, when a pressure wave strikes the diaphragm, it pushes it in, as shown in exaggerated form at (B). This causes button B to move in with it, compressing the carbon granules tighter together and thereby making better contact between their surfaces, decreasing their resistance accordingly, and allowing more current to flow through as shown at No. 2 in (D). If now a rarefaction follows the pressure wave, the diaphragm and button B spring outward as shown at (C). This diminishes the pressure on the carbon granules and they loosen up, thus increasing their contact resistance and allowing proportionately less current to flow through the circuit, as shown at No. 3 in (D). In this way, sound waves acting on the diaphragm will cause variations in resistance of the microphone and corresponding variations in the current through the circuit. If for instance, the letter "a" as in father

is spoken into the microphone, the sound waves are such that they will make the diaphragm vibrate back and forth and the resistance and current will vary as shown at No. 4 in (D). Other sound waves cause even more complex variations in the current.

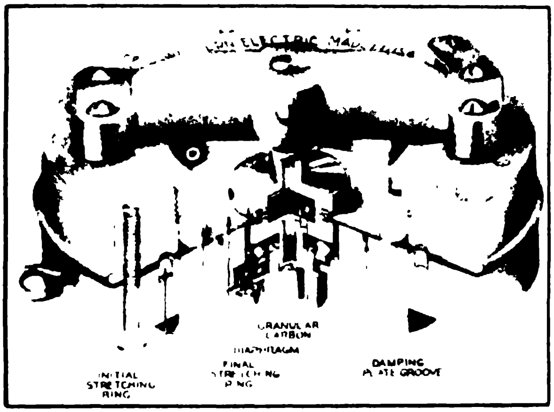
A microphone arrangement of this kind is very sensitive to changes in pressure on the diaphragm, that is, the resistance of the many contacts between the carbon granules varies greatly as the pressure upon them is changed. An idea of the sensitivity of these devices may be gained from the fact that the diaphragm in the ordinary microphone does not move more than a few ten thousandths of an inch, when a sound wave is acting on it. The current which such a transmitter can safely carry is very small, (ordinary microphones are designed to carry only from 15 to 35 milliamperes continuously depending upon the size), because of the fact that heat is developed at the contacts of the granules due to the resistance. At a current of 20 milliamperes, if the resistance is 200 ohms, $.02 \times .02 \times 200$ or .08 watt of electrical energy is being dissipated in the microphone in the form of heat. A limit is soon reached beyond which tiny electric "arcs" are developed between adjacent granules, the contact points of which become red hot and pack or stick together. When in this condition, the resistance does not vary much with change of pressure and the microphone becomes useless; also the intermittent arcs taking place cause spurts of current to flow through the microphone and when these are amplified by the usual audio amplifier they cause loud background sounds of a "scratchy" nature to be heard. A microphone that has become packed may usually be brought back to normal by disconnecting it and *gently* rotating or tapping it so as to shake up the carbon granules. The current in the microphone circuits of (A), (B) and (C) is a fluctuating unidirectional current when the microphone is spoken into, as shown at Nos. 1, 2, 3, and 4 of (D).

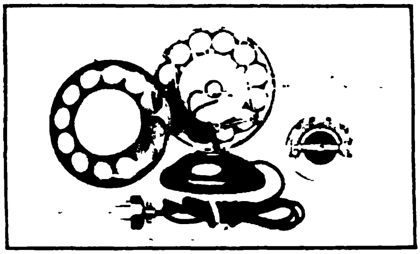
Experiment: The action taking place in a microphone may be demonstrated very simply by connecting up a 0-50 ampere d-c ammeter, a 6 volt storage battery, and two pieces of carbon, each about 2 inches square and one-eighth or more inches thick, all in series with each other as in (A) of Fig. 168. The carbon pieces are not connected together but are simply held face to face between the fingers. When a slight pressure is applied to press them together, the current will increase as shown by the ammeter reading. By quickly varying the pressure applied, the current and the ammeter needle may be made to fluctuate up and down quite rapidly. If the full 6 volt storage battery sends too much current through the circuit, tap off only one cell Use heavy wire for all the connections.

If a transformer T, is connected in the circuit as shown at (E), an alternating voltage will be induced across the secondary by the fluctuating direct current flowing in the primary shown at No. 4 of (D). This is in accordance with the laws of electromagnetic induction, for when the microphone current through the primary is decreasing, the magnetic field in the transformer is collapsing and an e.m.f. is induced in the secondary in such a direction as to tend to aid it in accordance with Lenz's law; when the microphone current is increasing, the magnetic field in the transformer also increases and the induced e.m.f. is in the opposite direction so as to tend to oppose it, in accordance with Lenz's law. Thus an alternating e.m.f. is being induced in the secondary winding. A *microphone coupling transformer* of this kind is usually employed for coupling a microphone circuit to a vacuum tube amplifier. Carbon type microphone circuits are usually energized by a 4½ or 6 volt bank of dry cells or a storage battery. A current regulating variable resistor of about 400 ohms and a 0-25 d-c milliammeter are usually included in the circuit to enable the operator to adjust the microphone current to the best operating value. Single-button carbon microphones are used extensively for speech alone, in public address systems, etc. Where the entire musical range of sound is to be transmitted as in orchestra programs, etc., the double-button type is employed on account of its better frequency characteristics.

By using two sections of carbon granules and making connections as shown in (F), some of the defects of the single-button carbon microphones are done away with. This is known as the ***double-button carbon type,*** and it is used extensively.

This microphone consists of a thin, light, duraluminum diaphragm stretched between the two cups containing the carbon granules. A sound wave striking the diaphragm causes it to vibrate back and forth on each pressure wave. This increases the pressure on the granules in one chamber and decreases the pressure in the other chamber an equal amount. Therefore, while the current in one side increases, that in the other side decreases. By arranging the transformer with a center-tapped primary winding as shown, it may be seen by actually tracing the path of the currents through the two halves of the winding and remembering Lenz's law for electromagnetic induction, that since they flow in opposite directions their effects are such that an increase in the current say in the upper half tends to induce an e.m.f. into the secondary in the same direction as a decrease in current in the lower half does, and vice versa. Thus for a given variation in current, the e.m.f. induced in the secondary is twice as great as would be induced by only one side of the microphone, or by a single-button microphone. This makes a more sensitive arrangement and it also eliminates distortion produced by "even" harmonics. Also the steady value of current flowing through the microphone does not magnetize the iron core of the transformer at all, since the





Courtesy Elect. Research Prod. Corp

Fig. 169—Left: Sectional view of popular type of double-button carbon microphone used for outdoor pickup work in radio broadcasting
Right: The same mike in its desk stand.

field produced by the steady current in one half of the primary winding is exactly neutralized by that set up by current in the other half of the winding, provided the current through the two buttons has been adjusted to be the same. This is usually done by means of a 200 or 400 ohm variable resistor connected in each outside leg of the circuit at the points marked "R". A current measuring jack J is usually provided in each outside leg of the circuit as shown, so that a milliammeter may be plugged into each side at intervals to check up on the current through each button. In the broadcast type microphone shown in Fig. 169, the operating current through each button should not exceed 25 milliamperes. The normal operating current is 20 milliamperes per button. The difference between the current in the two sides should not exceed 5 milliamperes. The resistance of each button is about 100 ohms, and as the two are in reality in series for voice currents, the output impedance of the entire microphone is taken as 200 ohms. It is only the *changes* in the currents in the two sides of the microphone that produce a resultant flux in the core and an induced voltage in the secondary winding. Changes of voltage of the battery will have no effect at all on the secondary voltage, since any such change affects the currents through both sides equally and so the circuit still remains balanced. The idea of balancing an increasing effect by a decreasing one, is used often in radio apparatus, since in general it eliminates distortion produced by even harmonics in the current or voltage. It is the basis of the push-pull system of connecting vacuum tube amplifier stages.

The induced voltage variations set up across the secondary of the microphone transformer T are usually so feeble that in most applications they are amplified by a 2 to 4 stage vacuum tube audio amplifier to bring them up to sufficient strength.

Two views of a very popular double-button carbon microphone used for many years in practically all American broadcasting stations and still used for most outdoor pickup work are shown in Fig. 169.

At the left is a cut-away section of the microphone. The thin duraluminum diaphragm is very tightly stretched and is placed a short distance from a flat metal plate. The stretching makes its natural vibration period very high so it is outside of the usual audio range encountered and will therefore prevent any blasting which would be caused by the sounding of a musical note of the same frequency as the resonant frequency of the diaphragm. Placing the diaphragm close to the flat metal plate gives a high damping effect due to the compression of the air between them. This action is assisted by the cushioning effect of the air in the damping plate groove shown. Both of these features of construction help to make the variations in microphone current conform exactly to the variations in the impressed sound waves at all sound frequencies from about 50 to 6,000 cycles, so that the microphone faithfully reproduces these sounds; that is, it has a good flat *frequency characteristic.* They reduce the sensitiveness of the microphone however, so that proportionally more amplification must be used in the circuits which follow.

On account of the stretched diaphragm, these microphones used for public address and broadcast studio work are much less sensitive than the ordinary telephone transmitter, but their fidelity and frequency characteristics are infinitely better. Whereas an ordinary telephone transmitter has a workable frequency range only from about 250 to 2700 cycles, a high grade double-button broadcast type carbon microphone has a flat frequency characteristic from about 50 to 6,000 cycles or more. In these, special polished carbon balls are used instead of irregular carbon granules. At least 2 or more stages of audio amplification are required to bring the output of microphones of this type up to loud speaker volume.

The two piles of carbon granules, one above the diaphragm and one below it are clearly shown in Fig. 169. At the right the complete microphone in its housing for desk mounting is shown. The microphone is suspended in the case by springs to absorb all shocks and jars. A three prong plug serves to connect it to a proper receptacle in the studio. Carbon microphones of the type shown above are not used to any extent in high-class broadcasting stations today, excepting for outdoor pickup work. The condenser and magnetic type microphones, which will be described later, have practically supplanted them for this work, on account of their much more perfect reproduction and freedom from hissing and other background noises which are present in carbon microphones due to small arcs which take place between the carbon granules. The advantage of the carbon type for portable outdoor pickup work is that since it is more sensitive than the above types it requires a less powerful and cumbersome amplifier. This is rather an important consideration in this type of work since the batteries required for these amplifiers are rather inconvenient to carry around from place to place.

236. Elementary radio telephone transmitter: We are now ready to consider the operation of a simple radio telephone transmitting system. The simple transmitter shown at (B) of Fig. 167 will enable us to transmit electromagnetic radiations in all directions. These will induce corresponding e.m.f.s and electric currents in receiving antennas erected in their path. Let us suppose that the generator in the transmitting antenna cir-

cuit supplies a high-frequency alternating voltage of steady value as shown by the voltage wave at (D) of Fig. 170. By this we mean that the maximum value of the voltage during each successive half cycle is exactly equal to that during the previous half cycle, although it is in the opposite direction. The current in the antenna circuit will be of similar waveform, and the train of electromagnetic waves radiated from the antenna will also be of similar wave-form as shown at (C) and (D) of Fig. 167. Consequently the e.m.f. induced in the receiving antenna will also look

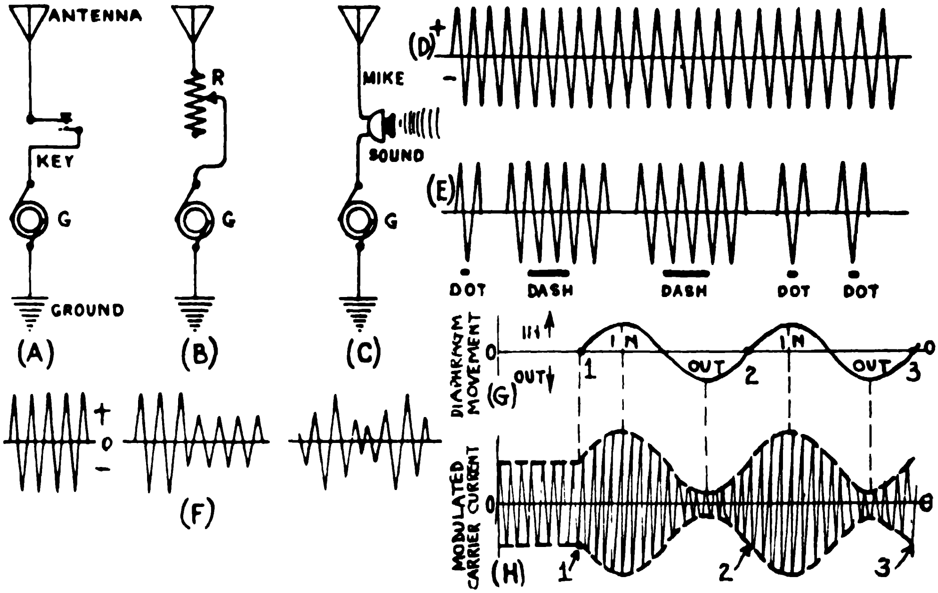


Fig 170—Modulation of r-f carrier current in radio telephony

like (D) of Fig. 170, but of course these e.m.f.s will be very much weaker in strength. Thus we have a continuous train of waves of uniform strength moving from the transmitter outward to the receiver. If we insert a switch or transmitter key in the antenna circuit as shown at (A), we can open and close the circuit at will, and thereby interrupt the flow of current and the train of waves sent out. If we opened and closed the switch according to some pre-arranged code of interruptions, forming short and long intervals of flows of current (dots and dashes), we could transmit messages which could be de-coded at the receiving end. The received e.m.f. or current waves in such a system would look like those at (E) of Fig. 170. Their representations as dots and dashes are marked directly below. This is the method used for continuous wave telegraphy.

If a variable resistor R were connected in series with the circuit as shown at (B), the current in the antenna circuit at each instant would be equal to the instantaneous value of the applied e.m.f. divided by the total antenna circuit impedance. With the resistor R at some fixed value,

the current would be as shown at the left of (F). If the resistor were set at a higher resistance value, the amplitude of the antenna current would be reduced, as shown at the middle of (F). Now suppose we varied the resistance of the rheostat back and forth from its maximum to its minimum value; the amplitude of the antenna current would vary likewise as shown at the right of (F). The successive transmitted fields would also vary in strength in exactly the same way and the e.m.f.s induced by them in any receiving antennas would also look exactly like them. By means of a variable resistor in the antenna circuit then, we have succeeded in varying the strength or amplitude of the antenna current, the radiated fields, and the induced e.m.f. and current in the antennas of the receiving stations. This varying of the strength of the antenna current is called "amplitude modulation". Another type of modulation in which the frequency of the current is modulated, is called "frequency modulation". This will not be considered here as it is not in general use at the present time.

237. Microphone as a modulator: It is not difficult to see that if we connect a microphone in the antenna circuit as shown at (C), the current in the circuit could be varied exactly in accordance with the movements caused by speaking against the diaphragm. This scheme can then be utilized for radio telephone transmission. Let us see how it operates:

When the microphone is not being spoken into, the diaphragm remains stationary and exerts a constant pressure on the carbon granules. Their resistance therefore remains constant and the successive cycles of the radio frequency current in the antenna circuit are of constant maximum amplitude as shown at the left of (F) in Fig. 170. If the diaphragm is pressed inward, the pressure on the carbon granules increases and the amplitude of the radio-frequency antenna current increases and remains constant at this value as long as the diaphragm is held in that position, as shown in the next series of current impulses at (F). When it is released the resistance and the current return to normal value. If the diaphragm is pulled outward, the pressure decreases, the resistance of the carbon granules increases, and the antenna current decreases and remains steady at the lower value shown at the middle of (F), as long as the diaphragm is held in this position. Suppose now that a 2,000 cycle tuning fork is set vibrating and placed in front of the microphone, so that its sound waves cause the diaphragm of the microphone to vibrate at a frequency of 2,000 cycles. In (G), if the line O-O represents the normal position of the microphone diaphragm when idle, then the sine-curve drawn above and below it represents the action of the diaphragm when the tuning fork is placed in front of the microphone. Thus the diaphragm assumes its maximum inward and outward positions 2,000 times per second and the resistance of the carbon granules varies accordingly. The high-frequency alternating antenna current flowing through the microphone will then vary in accordance with the wave-form shown at (H), changing from maximum strength to minimum and back to maximum again 2,000 times per second and the radiated energy varies accordingly, as shown at (H). If an "envelope" were drawn to enclose this representation of the current flow it would look like the dotted lines in this figure, having exactly the same shape as the curve at (G). The radio-frequency current is called the *carrier current*. The frequency of the microphone diaphragm, which in this case in 2,000 cycles per second, is the *modulating* frequency.

Suppose the station were transmitting with a carrier current frequency of 1,500,000 cycles per second (wavelength of 200 meters.) Then if this current is modulated at 2,000 cycles per second, one cycle of the modulation frequency lasts 1/2000 of a second. During this 1/2000 of a second the radio frequency carrier current goes through $1{,}500{,}000 \div 2000 = 750$ cycles. Consequently, if (H) were drawn accurately to scale, in one complete modulating wave from points 1 and 2, there would

be 750 cycles of the radio-frequency current, that is, during the time it takes for this particular sound or modulating wave to complete one cycle, this carrier current passes through 750 cycles.

From the foregoing it follows that it is possible to modulate the carrier current by the voice and thus transmit speech and music. Instead of placing a tuning fork in front of the microphone, one may talk or play into the mouthpiece. This will vibrate the diaphragm in accordance with the complex air vibrations produced when speaking or playing. When sounds from several sources are impressed on the microphone diaphragm simultaneously, the diaphragm movement at any instant is in accordance with the resultant air pressure wave produced by the combination of all of the individual air pressure waves caused by the different individual sounds at that instant. In practice, it is not practical to employ a circuit as simple as that shown at (C) of Fig. 170, for several reasons. First, in order to set up a maximum flow of current in the antenna circuit with a given applied voltage, the antenna circuit should be tuned to resonance. This is done by means of tuning inductances and high-voltage condensers (see Fig. 176) connected in the antenna circuit. The source of high-frequency voltage is coupled to the antenna circuit by means of a tuning transformer, (see Fig. 176). Also since the microphone can only handle a fraction of a watt of electrical power it cannot be connected directly in the antenna circuit where the heavy antenna currents are flowing. Practical transmitting circuits employ a multistage audio amplifier to boost the energy of the signal output of the microphone, as shown in Fig. 172. This goes to the modulator circuit where it is made to act upon the modulator tube which modulates the carrier current supplied by the oscillator, in accordance with the audio currents coming from the speech amplifier. The resulting modulated current is fed to the tuned antenna circuit. (See D of Fig. 171.)

There are several possible forms of modulating systems in use, and while all of them do not operate exactly as decribed above, the system we have considered is perhaps the simplest one for the beginner to understand. A detailed study of various oscillator and modulator systems will be taken up in a later chapter. Also, the "percentage modulation," or the degree to which the radio frequency, carrier current is varied in strength or "modulated" by the voice currents is a very important consideration in broadcasting of speech and music.

238. Practical transmission: Radio broadcasting stations which transmit speech and music, all operate more or less on the same general principle. It is true that not all stations are exactly alike, but for our purpose their individual differences need not be considered. In all of them, the programs are transmitted by means of carrier currents of very high frequency which are made to vary in strength (modulated) according to the intensity and frequency of the sound waves to be transmitted. A steady carrier current of very high frequency, (the frequency is determined by the operating wavelength of the station), is generated by means

of large vacuum tubes connected up as oscillators. This is shown at C of Fig. 171 and in Fig. 172A.

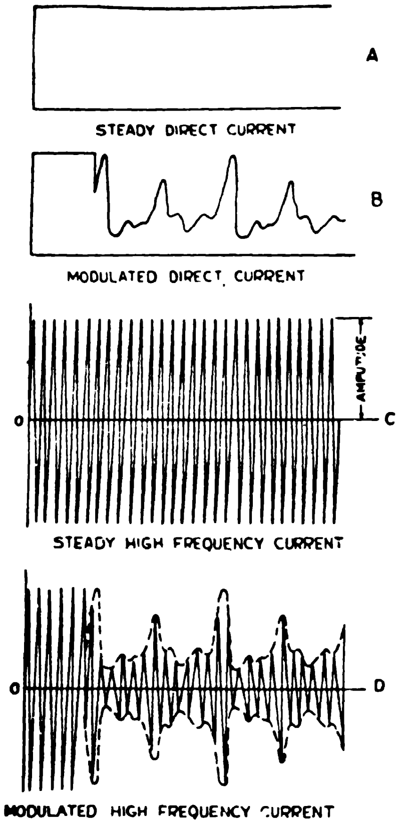


Fig. 171—Modulation of Direct, and High-frequency Alternating Current by Impressed Speech Frequencies

Notice that it is an alternating current and that the height or strength of the current during each cycle is exactly the same as during any other cycle. The fact that vacuum tubes suitably connected to a source of direct current and a special circuit, can be made to generate alternating currents of high frequency, (commonly called oscillations), is really the foundation of our present broadcasting systems. At A is shown the steady unidirectional current through the microphone when no sound is impressed on it. At B, the impressed sound waves cause the diaphragm to vibrate and the direct current in the microphone circuit is caused to vary in accordance with the sound.

If the voice current of B is allowed to regulate the flow of the radio frequency current of C, that is, to "modulate" it, the result is the modulated high-frequency current of D, called the modulated oscillating current. This current is no longer of constant amplitude, but its strength varies in exact accordance with the variations in strength and frequency of the voice current, or the spoken sounds. That is, the steady oscillating current has been modulated by the voice current. This is accomplished by a vacuum tube connected up as a *modulator tube.*

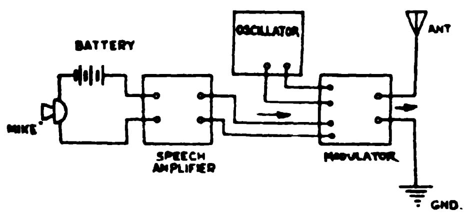


Fig. 172—Arrangement of main parts in the circuit of a transmitting station.

A simple analogy which may make this action clear, is to think of the high-frequency carrier current as a steady stream of water flowing out of the nozzle of a rubber hose. The voice current is represented by an adjustable opening in the nozzle,

which is made to vary continuously in size by squeezing it between the fingers. If this variation in the opening is made to take place rapidly, the diameter of the stream will be varying constantly to conform to the size of the opening in the nozzle, and the stream of water issuing from the hose will look somewhat as shown by the dotted outline envelope at D of Fig. 171.

The modulated oscillating current goes to the antenna circuit, where it produces radiations travelling in all directions. The frequency of these radiations is the same as that of the high-frequency carrier current, so that the frequency or wavelength of the station is controlled by adjusting the oscillator tube circuit. The actual broadcasting equipment is made up

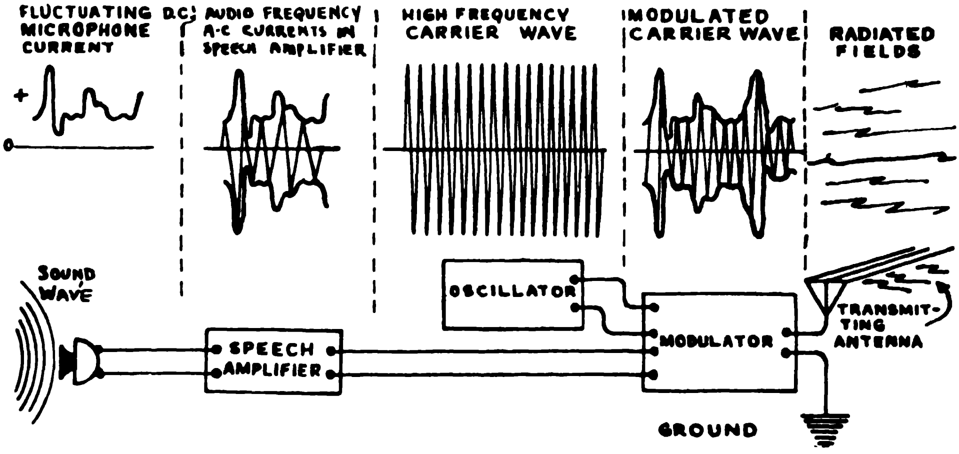
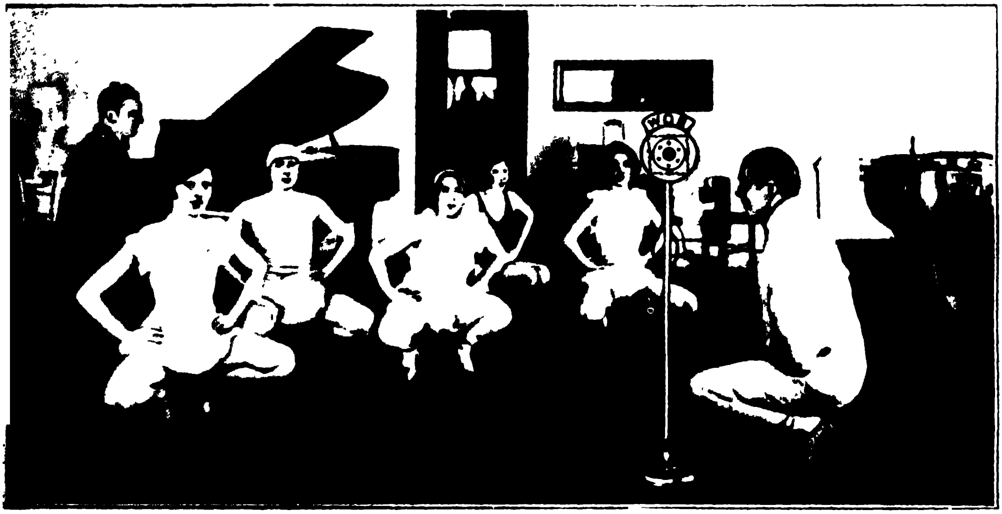


Fig 172A—Analysis of current changes taking place in various parts of a radio-telephone transmitter, starting at the microphone at the left

of the main units related to each other as shown in Fig. 172. In Fig. 172A, the types of currents existing in the various parts of this transmitting circuit are shown, starting with the fluctuating d-c microphone current at the left and ending with the modulated high-frequency fields radiated by the antenna at the right.

239. The broadcasting station: The speakers or artists perform in a studio (Fig. 173) where one or more microphones are located. This is usually a large room made sound-proof by means of special soundproof wall and ceiling construction, so that no outside noises will be picked up by the microphone and broadcast. The walls and ceiling are usually covered with a special acoustic celotex board having small air pocket holes punched in its surface. This acts as a sound absorber or deadener and helps to prevent echoes and reverberations which might cause blasting in the program reception. The floor is covered with thick rugs to deaden echoes and prevent footsteps from being heard. A small control unit

having key switches, signal lights, and an intercommunicating telephone to the control room enables the announcer to switch the different microphones on or off and keep the control and radio station operators advised of the progress of the program. All microphone and control circuits are carried in lead-covered cables laid behind the wall sound-proofing. Connection boxes are usually located along the baseboard near the floor for the microphone outlets. The auxiliary studio is similar to the main studio but usually smaller, and is used principally for readings and lectures. Many of the larger stations have several large studios to enable them to run rehearsals while some other studio is "on the air".



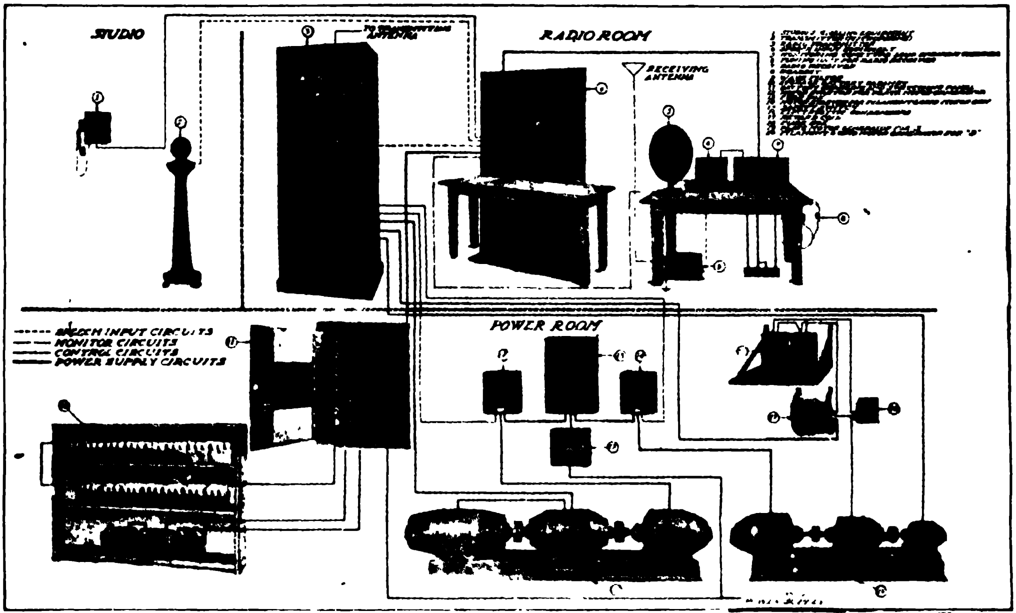
Courtesy Station WOR.

Fig. 173—Interior of a Radio Broadcasting Studio During the Transmission of an Early Morning "Daily Dozen" Program

Since the amount of current handled by the microphone is necessarily small, it must be amplified in order to be strong enough to properly affect the modulator tube when impressed upon it. This is done in the control room by a 3 or 4 stage *speech amplifier*. Between the microphone and the speech amplifier is the "*mixer*" panel into which terminate the circuits from the various microphones which may be used for picking up music from different directions and points. The operator can boost or tune down the output of any one microphone at will, thus securing the best combined sound output. Since there is very wide variation between the loudness of voices and of musical instruments, the speech amplifier must be capable of adjustment so that when a particularly loud part of a program comes through, the operator can cut down on the control and not allow as much current to pass through the amplifier. This is necessary in order to avoid distorted and unnatural reception, caused by overloading of both the transmitting and receiving apparatus. In most stations,

it is possible to reduce the amplification down to a very small fraction of maximum volume. This operation is accomplished continuously by a station operator and is known as *monitoring*. If the monitor is not quick and constantly on the alert, the loud notes of an orchestra may come in like thunder and the low, soft tones may be lost entirely. From here the circuit goes to the main control room, in which is a relay switching system to other studios, and a two stage line amplifier.

The next part of the transmitter is the modulator. This is a vacuum tube device and in the usual plate-power-variation, or Heising constant-



Courtesy Western Elect. Co.

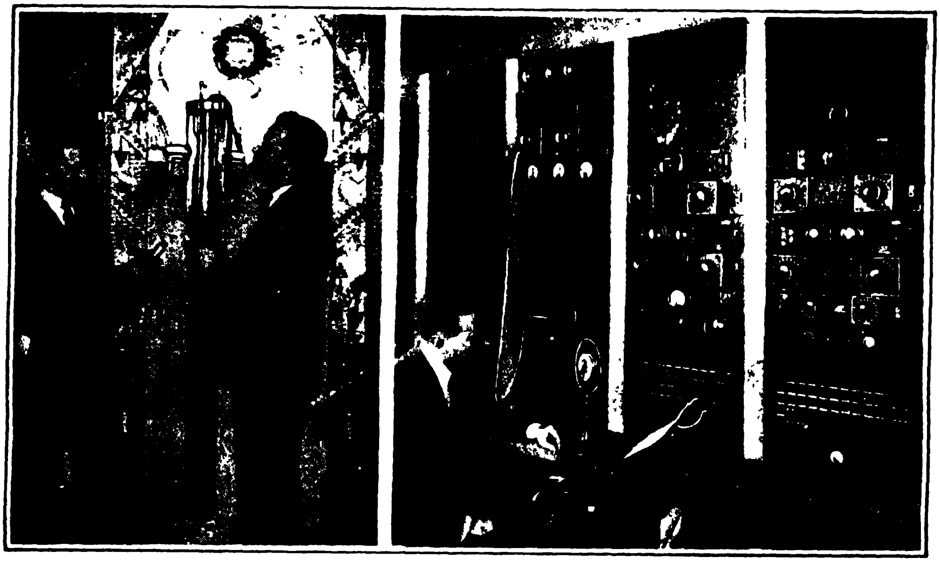
Fig 174 —Pictorial view of the apparatus in a broadcasting station of medium size.

current method of modulation, it varies the plate power going into the oscillator tubes. In it, the plate voltage applied to the oscillator, (whose frequency is the "carrier" or high-frequency of the station), is varied by the audio-frequency modulating voltages. Since the oscillator current, and hence the antenna current, is proportional to the plate voltage, this current will vary, or be modulated by, the audio variations. The oscillator tubes are usually connected in a Meissner circuit for generating high-frequency oscillations.

The plate circuits of the vacuum tubes used as oscillators must be supplied with high-voltage, direct-current power. The filaments of all the tubes take quite a large current at low voltage. In order to provide this, some stations employ motor-generator sets operating directly from the electric light and power lines. The output passes through a coil and condenser filter combination designed to take out the commutator ripples.

Other stations transform low voltage a-c to high voltage, and then rectify it, changing it to direct current by special forms of large vacuum tubes called Kenotrons.

The station equipment also includes a special super-heterodyne receiving set tuned to the wavelengths used in commercial ship work. One operator is constantly on duty at this set to listen for possible SOS distress signals, so that the broadcast station can be taken off the air immediately upon their reception, to avoid possible signal interference.



Courtesy National Broadcasting Co

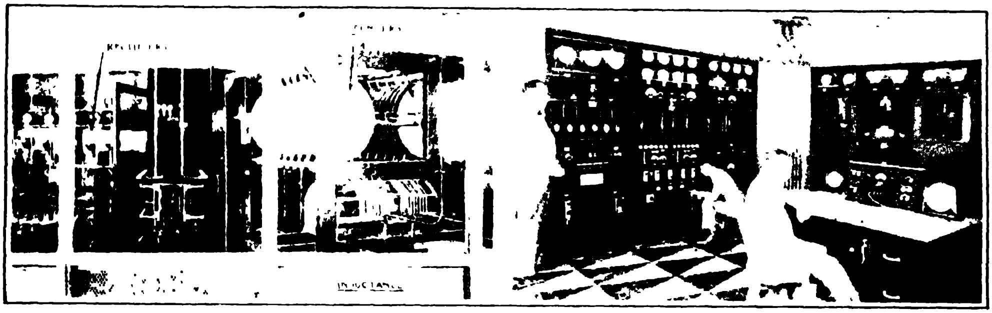
Fig. 175—Left: $1500 worth of vacuum tubes used in station WEAF At the left is the smallest size tube used in the station At the right is a UV862 tube used for generating the high frequency carrier current. Water is circulated in the metal jacket at the bottom
Right: Operating control room at WEAF At the left center is the oscillograph on which a continuous moving picture of the station output may be observed

Fig. 174 shows a pictorial view of the apparatus in a modern broadcasting station. The various parts and circuits are labeled for easy reference. This is the complete equipment for a 1,000 watt station. The storage batteries are used to operate the speech amplifier.

At the left of Fig. 175, 1,500 dollars worth of vacuum tubes used in a transmitting station are shown. Mr. Gray, in charge of station WEAF is holding the smallest size tube used in this station, and Mr. Guy is holding a UV-826, the largest size tube used in modern radio stations. This station broadcasts with a power of 50,000 watts, and large water-cooled tubes of this kind connected as oscillators produce the high-frequency carrier current. At the right is shown the operating control room apparatus at this same station. At the left-center of this illustration may be seen the oscillograph on which a continuous moving picture of the station

output may be observed so that the attendant may accurately control the degree of modulation and keep an accurate check on the quality of the transmission at all times.

At the left part of Fig. 176, may be seen the rectifier tube system of station WEAF, which makes available 12 amperes at 18,000 volts d-c for the plate circuits of the oscillator tubes. At the upper right of this part of the illustration are the huge aluminum disc high-voltage tuning condensers and below them the tuning inductance wound with copper strips on a wooden framework. At the right is shown a section of the main transmitter room and the operator's control desk, from which the amplifying and switching equipment is controlled. The low-power units,



Courtesy National Broadcasting Co

Fig. 176—Left: Rear view of part of station WEAF transmitting equipment The rectifiers are at the left The huge high voltage tuning condensers and tuning coil are at the right.
Right: Section of the main transmitter room and operator's control desk

including modulating and frequency control-devices, are at the left; in the left center is the 50 K.W. power amplifier; in the right center is the 20,000 volt high-power rectifier and at the extreme right are the power control equipment and dummy antenna system used for test purposes.

240. Electrical transcriptions: Although broadcast programs reproduced from the ordinary phonograph disc were common in the smaller stations even a few years ago, the latest improvements in the method of recording and reproducing sound programs on high quality phonograph records has increased the use of the special disc records as a source of broadcast station programs instead of having the artists perform personally before the microphone. When used for radio broadcasting purposes, they are called *electrical transcriptions.* The method employed, is simply to use an electrically driven phonograph turntable with an electrical pickup unit (see Art. 541) playing from the record and feeding directly to the speech amplifier in the station. This modulates the carrier current in the usual way.

The latest technical developments in the art have made possible the inscribing of a tone range extending from 30 to 9000 cycles in these discs.

This is far greater than can be distributed from studios to outlet stations by any other means. At the same time, facilities have become available to broadcasting stations for reproducing slow-speed transcriptions without the speed changes heretofore characteristic of phonograph reproductions. The combined use of these two major developments in this field, which have come to the forefront only lately, have won instant recognition by program sponsors and broadcasting stations alike. The electrical transcription method of broadcasting enables those smaller stations located, either in or away from the large cities, which cannot conveniently obtain the services of high-grade performers, to broadcast from records which were made in the cities by these highly paid artists. Thus the cost of a performance by such artists is spread out over a large number of duplicate records made and rented to the small stations. This enables them to offer programs of a quality and appeal which they would otherwise be unable to afford.

241. Remote control: If the broadcasting originates at some point away from the station, as in the case of a football game or other event, the microphones and usually a speech amplifier are installed at the field and special wire telephone lines are run to the transmitting apparatus in the broadcasting station. Usually, existing telephone lines are rented from the telephone company. Some stations employ a portable short wave radiophone transmitter of low power which is sent to the scene of activity, and the program is transmitted by radio directly from there to the main broadcasting station, where it is received and re-broadcast with increased power.

242. Artificial sound effects: Practically all broadcasting noises accompanying plays, special programs, etc., must be made to order in the studio. A most critical audience, often numbering millions of people, lends careful ears to the synthetic sounds. The action of a radio play is as broad as that in a theater, and the faithfulness of the illusion depends largely upon synthetic sounds.

An airplane engine, if picked up outdoors, would be heard for what it is. Inside a studio, the reverberations and echoes, clashing against the walls, would give the radio listener nothing but noise. But an old-fashioned foot-pump organ makes a noise exactly like an airplane motor and is used to create this effect in radio broadcasting.

The "zz-z-zziii--nnn-nngg-g-gg" of a bullet is simulated by plucking the steel string of a guitar. Hoof beats are hard to fake. Fire is simulated by cracking a bundle of canes together. Hissing water is easily imitated by letting off compressed air. If a house collapses, a box of bricks are allowed to fall down a chute. A firecracker celebration on the roof gives the radio listener an idea that a battle is taking place. Machine guns are simulated by riveting machines. Many ingenious devices have been developed for producing sounds of all descriptions and they are worked out so well that even careful listeners can never tell the difference.

242A. Chain-station hookups: It is often desirable to broadcast a single elaborate broadcast program over a number of stations simultaneously, to cover a large area,—especially for advertising purposes. The method which has been applied most successfully for achieving widespread distribution of a broadcast program, is that of interconnecting a number of stations by suitable telephone wire circuits so that they all broadcast the same program simultaneously. This is called a *chain-station hookup*. These broadcasting stations, located at strategic points scattered over the wide area to be served, permit the large majority of listeners to receive the program just as satisfactorily as they receive local programs.

In a chain-station hookup, the audio-frequency currents from the microphone which picks up the program, after passing through the control operator's amplifier, are delivered to a system of telephone lines which in many respects resembles an electric power-distributing network. Trunk wires go out from the program center to various parts of the country, and from these at appropriate points, connecting wires branch off to the broadcasting stations. Telephone repeaters are placed in the circuits at suitable points to amplify the currents so that they may reach the broadcasting stations without material loss in volume. As has already been pointed out, distortion of the telephone currents must be very small, or the faithfulness of reproduction at the receiving points will be spoiled. On this account, the very best kinds of telephone circuits and associated apparatus are employed.

REVIEW QUESTIONS

1. Explain with the aid of diagrams, what your understanding is of the way in which electromagnetic radiations are produced and sent out from the antenna of a radio transmitting station.
2. What is the induction field around a transmitting antenna? What is the radiation field?
3. Is it the induction field or the radiation field that is useful in radio communication? Why?
4. What is the phase relation between the radiation electrostatic field and the radiation electromagnetic field? How are they related?
5. State one reason why radio signals can be transmitted further with a given expenditure of power by means of very high frequency radiations (short waves) than they can by the use of lower frequencies.
6. Explain an application of signalling by means of the induction magnetic field around a conductor.
7. Draw a diagram showing the relative directions of the radiated electrostatic field from an antenna and its associated magnetic field in space.
8. How does a doublet antenna differ from an ordinary grounded

antenna? Why are doublet antennas used extensively in short wave work and not for broadcast band (200 to 600 meters) reception?

9. What is meant by the "radiation resistance" of an antenna? Would a good transmitting antenna have a high value of radiation resistance or a low value? Why?
10. Explain the construction and operation of the single-button carbon microphone.
11. Explain the construction and operation of the double-button carbon microphone.
12. Why is a carbon microphone of the type used for broadcasting purposes less sensitive than the transmitter used in ordinary telephones?
13. Explain how the changes in the current flowing through both sides of a double button microphone are made to add their effects in the split primary of the microphone transformer
14. Why is it that an alternating e.m.f. is induced in the secondary winding of a microphone transformer when the fluctuating direct current from the microphone flows through its primary?
15. Draw a diagram of a simple arrangement whereby you could transmit sound impulses by means of a microphone, a source of steady high-frequency r-f current, and a suitable energy radiator. Explain its operation, bringing out the detailed explanation of how the microphone modulates the r-f current.
17. Draw an outline diagram showing the connections of the following main parts of a radio broadcasting station; microphone, speech amplifier, oscillator, modulator, and antenna system. Explain in progressive order the actions taking place, from the microphone input to the outgoing modulated waves.
18. What is the purpose of "monitoring" in a broadcasting station?
19. Why are broadcasting studios lined with special sound deadening or absorbing materials?
20. Explain the method of broadcasting by means of "electrical transcriptions".
21. How are programs originating at places outside of the broadcasting studio, broadcast?
22. Why must a speech amplifier be used at the point of the pickup in a case of remote program pickup of this kind?
23. What produces such sounds as the whirring of an engine, firing of guns, noise of a locomotive, etc., which are heard in a broadcast program originating in the studio of a broadcasting station?
24. What is the electrical difference between a "short wave" transmitting station and a "broadcast band" transmitting station?
25. A broadcasting station is transmitting at a wavelength of 250 meters. What is the frequency of the carrier current generated by its oscillator tubes?

CHAPTER 16.

THE RECEIVING STATION, DETECTION WITH CRYSTALS

HOW THE ENERGY IS RECEIVED — INDUCING VOLTAGE IN THE RECEIVING ANTENNA — NECESSITY FOR TUNING — SINGLE CIRCUIT TUNER — TUNING THE SECONDARY CIRCUIT — TWO CIRCUIT TUNER — GAIN PRODUCED BY TUNED CIRCUIT — CHANGING THE ELECTRICAL ENERGY TO SOUND — EARPHONE OPERATION — NEED FOR THE DETECTOR — THE CRYSTAL DETECTOR — DETECTOR ACTION — THE CARBORUNDUM CRYSTAL DETECTOR — CONSTRUCTING A CRYSTAL RECEIVER — OPERATION OF THE ENTIRE RECEIVER — MEASURING CRYSTAL DETECTOR CHARACTERISTICS — LIMITATIONS OF CRYSTAL RECEIVERS — REVIEW QUESTIONS.

243. How the energy is received: The purpose of this chapter is not to present a complete description of modern sensitive receiving sets, but simply to set before the student an elementary conception of how the radio energy is received at the receiving station and what must be done to it to convert it most efficiently into a form that we are able to hear. While it is true that receivers with crystal detectors are used very little at the present time, the author has found that the student can gain a great deal of fundamental theory concerning radio receivers by studying a simple crystal receiver at first. By doing this, most of the theory of tuning and detector action may be developed simply, without the necessity for introducing any of the complications brought in by vacuum tubes. After these receiver fundamentals are firmly grasped, the study of vacuum tube receivers can be pursued with ease.

It will be remembered from the previous chapter, that in the broadcasting station we allow the sound waves to act on the microphone, producing corresponding variations of an electric current, as shown at the left of Fig. 172A. This varying microphone current is amplified by a speech amplifier and fed into the modulator circuit where it is made to modulate or vary the strength of the individual cycles of the radio frequency carrier current generated by the oscillator. The resulting carrier current is modulated or varied in strength somewhat as shown at D of Fig. 171, and at Fig. 172A, depending of course on the particular sound transmitted. This modulated radio-frequency energy is coupled to the antenna or radiating system. Here it sets up an electric field that radiates out in all directions at the rate of 186,000 miles or 300,000,000 meters, per second. Since the energy spreads out over a wide area, the *amplitude* of the fields varies inversely as the distance from the transmitting antenna. At twice the distance their amplitude is halved, at four times the distance it is one-quarter as much, etc. The radiated energy is in the form of a rapidly fluctuating electrostatic field with its accompanying magnetic field. In practical transmission, there is also a decrease in strength due to the fact that whenever the waves strike any object in which they can produce electric current (such as the steel framework of a building), currents are produced at the expense of the energy of the waves, and

heat up to a minute degree, the material in which they flow. This dissipation of energy acts simultaneously with the inverse distance effect to reduce the strength of the waves and the signals received, as the distance from the transmitter increases. The latter effect is especially great around large cities like New York, Chicago, etc., and is one of the reasons for poor "distance" reception in these cities.

It should be remembered that these fields go through every non-metallic body which may be in their path. If now, a conductor of any kind is erected in their path, as for example the aerial wire shown in Fig. 177, a voltage will be induced in it by the rapidly passing fields. In the case of the reception of very high-frequency fields (short wave work), the antenna may consist merely of a wire, as shown at Fig. 166, but with the receiving apparatus at the center instead of the generator. This is called a "doublet" antenna. In order to be efficient for broadcast band reception, the length of such a doublet would have to be too long to be practical. Therefore an antenna or aerial wire of the form shown in Fig. 177 is commonly erected.

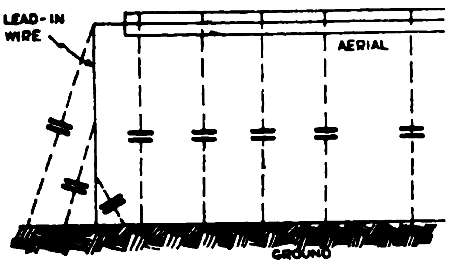


Fig. 177—How the antenna wire forms a condenser with the earth or ground.

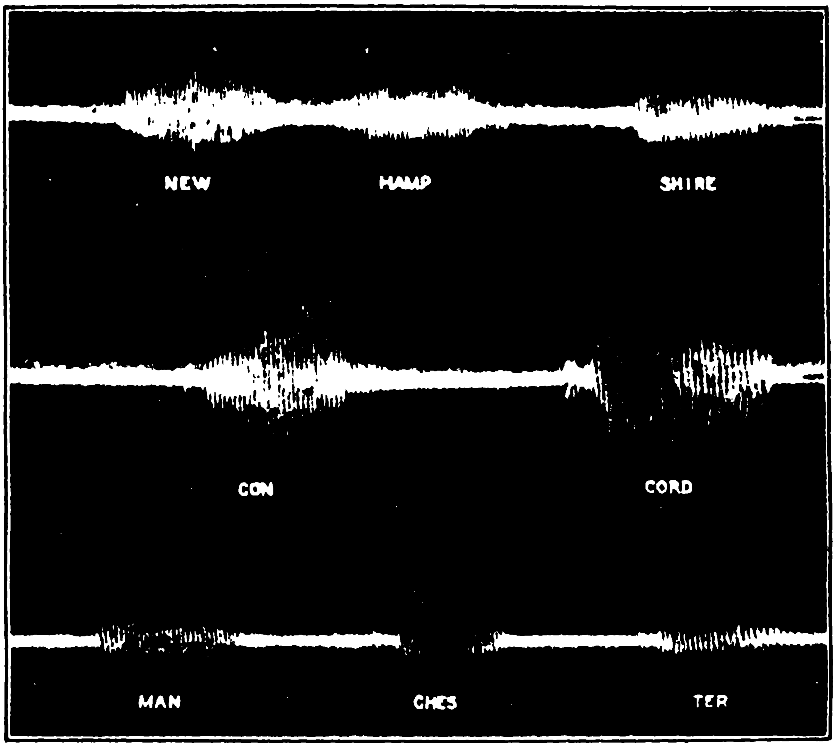
Note: The words *aerial* and *antenna* are used interchangeably by the layman, although accurately speaking, the top or elevated portion of the antenna is the *aerial*, and that portion which completes the electrical connection between the elevated aerial portion and the instruments is the *lead-in*. The *antenna* is the entire system consisting of the aerial and lead-in together.

The antenna usually employed consists of a flat-top aerial portion which is connected to the radio receiver by the *lead-in* wire. The other side of the receiver circuit is connected to the ground either by connecting it to a metal plate buried in the ground, or connecting it to a water pipe which serves the same purpose, since the pipe runs through the ground for a considerable distance and therefore makes electrical contact with it. It is evident from Fig. 177, that the combined aerial and the lead-in wires form one plate of a condenser and the earth and ground wire form the other. The distributed capacity action thus set up is illustrated by the small condensers shown distributed at intervals between the ground and these parts in this illustration. The capacitance of a simple receiving antenna of the type shown and used for radio broadcasting reception, may be as much as 150 to 300 micro-microfarads (200 mmfd. being a good average). The inductance of the wire may be as much as 50 to 100 microhenries and the total resistance may be anywhere from 25 to 100 ohms, depending on the length of the wires, resistance of the ground contact, etc.

Note: The arbitrarily selected *standard receiving antenna* which is used in measurement work is an antenna of 4 meters effective height, 25 ohms resistance, 200 micro-microfarads capacitance and 20 microhenries inductance. Such a standard antenna may easily be constructed artificially for test purposes (except as to height).

244. Inducing voltage in the receiving antenna: We may consider the voltage induced in the aerial circuit to really be caused by the following two actions:

First, the passing electrostatic fields which are alternating in direction very rapidly (at a rate equal to the carrier frequency of the broadcasting station), produce distortion of the electron orbits in the air dielectric around the antenna system. This causes unbalanced electrical forces which tend to cause motion of the free electrons in the antenna wire in contact with the atmosphere; in other words an e.m.f. is induced in the wire. The e.m.f. will vary in direction and strength exactly in accordance with the



Courtesy American Tel & Tel Co

Fig. 178—Oscillograph photograph of a carrier wave modulated by the words "New Hampshire," "Concord," and "Manchester" Notice the rapid and complex variations of the current.

variations in the passing fields, which as we have seen, may be represented by the modulated curves at D of Fig. 171. The action is practically the converse of the action taking place during the charging of a condenser by an applied e.m.f. as in Fig. 83.

The other portion of the induced e.m.f. may be considered as being caused by the electromagnetic induction set up by the rapid movement of the passing electromagnetic field. The high-frequency e.m.f. induced in the antenna circuit will cause a surge of electrons rapidly up and down the circuit at a frequency equal to that of the carrier wave of the transmitting station, the strength of the individual cycles varying in accordance with the modulation impressed on the carrier wave, as shown at D of Fig. 171.

The electrons surge up and down very rapidly in the antenna circuit, a surge taking place every time a wave of radio energy passes the

antenna. This flow of electrons constitutes a flow of electric current. Fig. 178 shows the complex variations in the current set up in an antenna circuit by the passing waves of a single broadcasting station when the carrier wave of the station is being modulated by the words "New Hampshire", "Concord" and "Manchester" spoken into the microphone in the studio. It should be remembered that this current is an exact duplicate, as regards wave-form of that sent out from the broadcasting station, that is, the rises and falls of the e.m.f. and current in the receiving antenna circuit will follow exactly those in the transmitting antenna, the only change being that the voltages set up in the receiving antenna are unbelievably small, being in the order of a few millionths of a volt (microvolts), see Art. 348.

A connection to the earth is not necessary for the reception of radio signals. Anything which will serve the same purpose as the ground does in forming the other plate of the condenser made up by the antenna circuit, will operate just as well. We usually employ a connection to the ground for this purpose simply because this can be conveniently obtained by simply connecting to a conveniently located water pipe. This saves us the trouble of erecting a counterpoise. In some radio receiver installations, as in the case of a receiving set in a moving automobile or aeroplane, it is not possible to make an actual connection to the ground. The "ground" side of the antenna circuit may be connected to a wire or network of wires supported a short distance above the earth and insulated from it. This network of wires then acts as one plate of a condenser (taking the place of the ground) and the antenna as the other plate. It is called a *counterpoise* ground. The counterpoise is usually located directly under the antenna. When a radio receiver is operated in an automobile, a short wire is erected in the roof of the car, and the metal frame and body of the car are used as a counterpoise ground. In an aeroplane, the engine frame and bracing wires are electrically connected together and used as a counterpoise; a trailing copper wire usually being employed as an antenna. Instead of a suspended antenna wire and counterpoise, two metal plates or sheets of copper wire netting separated and insulated from each other may be used, one as the antenna and the other as the counterpoise. This scheme is also used in some "automobile receiver" installations as we shall see in Art. 532. The important point to remember is that the ordinary capacity-type antenna system really consists of two conductors separated from each other, and so arranged with the receiving equipment that electrons can surge back and forth through the circuit from one of these conductors to the other many times every second, this constituting a flow of current. These two conductors may take any one of many forms. We ordinarily make a connection to the earth simply because this saves us the trouble of erecting a counterpoise. In many cases where the earth is dry and rocky and therefore has quite high resistance, a correctly designed counterpoise ground (being of much lower resistance) will greatly improve the reception. Some receivers (especially those electrically operated) apparently work without any connection to the ground terminal of the set. In this case a counterpoise ground is being formed by the wires in the set, by the capacity action between the wires in the set and the ordinary ground, or by capacity to the electric light circuit which comes to the receiver and which always has one side grounded.

If a loop or coil antenna is used at the receiving station, the voltage induced in it is due almost entirely to the action of the magnetic field alone. This will be discussed in Art. 607 when dealing with "loop antennas."

245. Necessity for tuning: Up to this point in our discussion, we have assumed for simplicity that the only voltage induced in our receiving antenna is that caused by the action of the radiated fields of the one station we desire to receive. Although it may seem surprising at first, it is nevertheless true that practically every radio station in the entire world

which is broadcasting radiations of any frequency (whether the transmission be that of code messages or sound programs), will induce voltages of corresponding frequency in our antenna circuit and therefore cause currents to flow up and down in it. The radiated fields from a 5-watt station located 1000 miles away are impinging on our antenna just as well as those of a local 50,000 watt broadcasting station (unless they have been greatly weakened by some material obstruction on the earth causing a shielding or screening effect; or are affected by skipping or fading). Although the induced voltages and currents caused by comparitively weak or distant stations will be very much weaker than those induced by powerful or local stations, nevertheless they are there just the same. Of course, we do not hear all of these stations with present day receivers because

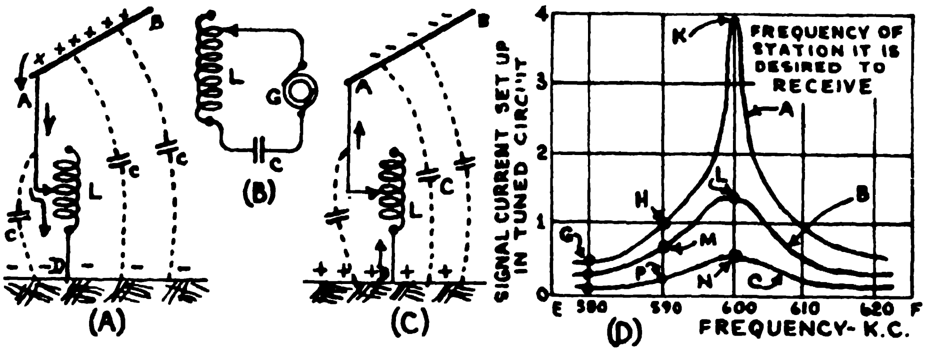


Fig. 179—Simple radio receiving circuit, and the effect of resistance in the tuned circuit.

many of these signals are so weak when received, that the receiver does not amplify them enough to make them heard. Nevertheless, there will be enough comparitively strong signals set up in any antenna which we might erect, to cause several of the stations to affect our receiving equipment strongly enough so they will all be heard at once, and thereby interfere with the clear reception of any one of them at a time. *Therefore, since we want to hear only one station at a time, we must in some way weaken the signal currents of all of the stations it is not desired to hear and allow the currents of the station it is desired to hear to flow through the receiving equipment with as little loss of strength as possible;* in fact in modern radio receivers we even amplify the signal we desire to hear by means of vacuum tube amplifiers. Fortunately, this can be accomplished by employing the principles of electrical resonance studied in Arts. 172 to 177. (The student is advised to review these articles at this time in order to refresh his memory on the theory of both series and parallel resonance.) All radio transmitting stations in the same vicinity send out their signals at different carrier current frequencies. Therefore the voltages and currents set up in our simple receiving antenna system of Fig. 177 will also all be of these different frequencies. We know from our

previous work, that a series-tuned circuit offers a very low impedance (actually equal to its resistance) to the flow of current of the frequency to which it happens to be tuned to resonance, and offers a much higher impedance, in varying degrees, to the flow of currents of all other frequencies above and below this. Conversely, a parallel-tuned circuit offers a very high impedance to the flow of current of the frequency to which it happens to be tuned to resonance, through the circuit in which it is connected. It offers a much lower impedance, in varying degrees, to the flow of currents of all other frequencies above or below this value.

246. Single-circuit tuner: We can use the principle of series resonance to produce the desired separation of signals by means of the simple arrangement shown at (A) of Fig. 179. Here an inductor L, commonly called a tuning coil, is connected in the antenna circuit. This, together with the capacitance between the antenna system and ground (shown by imaginary condensers C), forms a series-tuned circuit, the resonance frequency of which is found from equation (20) in Article 173, which is $f = \frac{1}{2\pi\sqrt{LC}}$ where L is in henries and C is in farads. This may also be expressed as: $f = \frac{159{,}000}{\sqrt{LC}}$ where C is in microfarads and L is in microhenries.

This circuit is considered to be a *series circuit* because the signal voltage is induced in a part of it (in the antenna wires and lead-in) and is therefore in series with the rest of the circuit (see article 171). The circuit of (A) may be drawn in simplified form as shown at (B), where the induced voltage in the antenna circuit is considered as being supplied by the high-frequency a-c generator G.

By means of either of the equations above, we could calculate the inductance tuning coil L would have to have, which, when acting in the circuit with antenna capacitance C, would produce resonance in the antenna circuit at the particular frequency of the signal it is desired to receive. (Actually the antenna circuit has some inductance which must be added with L when making this calculation.)

Assuming that this value of inductance were used and connected as shown, when the passing fields cause an electron flow downward through the circuit into the ground, the ground becomes charged excessively *negative* and the aerial wire AB becomes charged *positive* due to a corresponding lack of electrons, ([A] of Fig. 179). When the next change in direction of the field takes place, the aerial becomes charged negatively and the ground is charged positively by the flow of electrons upward as shown at (C). Consequently, we have in this series tuned antenna circuit, a rapid surging of electrons (current flow), first from the aerial through the tuning coil to the ground, and then in the reverse direction from the ground through the coil to the aerial, over and over many times a second.

Since the series tuned circuit offers a low impedance to the flow of electrons or current having the same frequency as that to which it is tuned, the voltage induced in the antenna by the one station of this frequency is able to send a comparitively large flow of current through the circuit,—and the station will be heard loudly. Since a much higher impedance is offered to the flow of currents of all other frequencies above and below this, the voltages induced in the antenna by all other unwanted stations will only be able to set up comparitively weak currents in the antenna circuit

so they will not be heard at all. (In practice, absolute separation of stations cannot be accomplished by a single tuned circuit, due to the fact that the resistance of the wires, ground contact, etc., broaden the tuning so that the wanted station does not set up so much more current than the unwanted stations as we might suppose. Therefore we find modern radio receivers using as many as four or more tuned circuits to obtain satisfactory separation of the received signals.)

The arrangement thus far employed at (A) and (C) would enable us to receive strongly, that station for which the particular values of L and C employed made the circuit in resonance. If we wanted to receive a station transmitting on a different frequency, the value of either L or C or both would have to be changed. In the old single circuit receivers, it was customary to make the inductance of the tuning coil adjustable, in order to tune the various station frequencies. In one form of tuning coil employed, a contact was arranged to slide over the wire and therefore vary the number of turns of wire and the inductance in the circuit. The coil was built somewhat as shown at (A) of Fig. 79, and was known as a *single circuit tuner*.

247. Antenna resistance and selectivity: Since the resistance of the entire antenna and ground wire and that of the contact between the earth and the water pipe, (or whatever is used for actual connection to the earth), is directly in the tuned circuit in the single-circuit system just described, the tuning is rather broad, that is, there is no great difference between the strength of the current set up by the signal of the *wanted* station and the currents set up by the signals of all the other *unwanted* stations.

Since the current flowing in the circuit at resonance is equal to the signal e.m.f. induced in the antenna divided by the high-frequency resistance of the total antenna circuit, it is evident that if this resistance is high we may not gain very much by tuning, for even at resonance the high-frequency ohmic resistance of the circuit might be high enough to keep the current set up by the wanted station from being very much stronger than that set up by the unwanted stations. In order to obtain sharp tuning therefore, it is evident that the ratio of the *reactance* to the *resistance* of the tuned circuit must be made high.

The effect of broad tuning may be seen from (D) of Fig. 179. Three resonance curves A, B and C are plotted for the tuned circuit. These show the values of the current which equal signal voltages of various frequencies will set up in the tuned circuit, (corresponding to the signal voltages received from several equally distant and equally powerful transmitting stations), for three different values of resistance of the tuned circuit. Let us suppose the circuit has such a value of inductance L and capacitance C that it is tuned to resonance at 600 k.c. Then considering the sharp tuning condition represented by curve A when the resistance of the circuit is kept low, a station transmitting on 580 k.c. would set up current in the receiving antenna circuit represented by the height of point G above the axis line E F (equal to about 0.5 arbitrary units of current); a station at 590 k.c. would induce a larger current of one unit represented by H, a station transmitting at 600 k.c. (the frequency to which the receiving circuit is tuned) will set up the largest value of current (4 units of current represented by K). Stations of higher frequency such as 610 k.c., 620 k.c., etc. will set up lower values of current as shown. Therefore, the current set up by the station to which the circuit is tuned (4 units) is 4 divided by 1, or 4 times as strong as the 1 unit of current set up by an unwanted station transmitting at say 590 or 610 k.c. Evidently the wanted station will be heard much more loudly than the unwanted station. The reason for this difference of current is of course due to the different reactance and impedance which the tuned circuit offers to the flow of currents of different frequencies. Referring back to the right of Fig. 116, where we considered in detail how the reactance of a series tuned circuit changes as the frequency is varied, we find that as we decrease the frequency from that at resonance, the capacitive reactance

increases greatly (since now the condenser does not charge and discharge as many times per second as before and therefore there is less current in the external circuit between its plates); and as the frequency is raised above that of resonance, the inductive reactance increases greatly (due to a greater value of the induced counter—e.m.f.), and thereby reduces the current.

If now our tuned circuit had quite some resistance, the current at resonance (curve B), represented by point L, would be much less than in the previous case, being only 1.5 units now. Likewise the current at all other frequencies is much lower than before due to this greater resistance, as shown by the fact that curve B is lower at all points than curve A. The current set up by the station to which the circuit is tuned (1.5 units at point L) is now equal to only $1.5 \div 0.75 = 2$ times as strong as that set up by an unwanted station transmitting at a frequency 10 k.c. from that to which the circuit is tuned (point M). Therefore, it is evident that in this case since there is not very much difference between the strength of the current set up by the wanted station and that of an unwanted station differing in frequency by 10 k.c., both of them will probably be heard, the program of one interfering with that of the other. If the circuit had even more resistance, its tuning curve might be represented by curve C, and the current set up by the wanted station (point N) would be only about 1.5 times that set up by an unwanted station 10 k.c. away (point P), so that both stations would most certainly be heard together with practically the same loudness. Notice that the effect of having a tuned circuit with appreciable resistance is to reduce the value of the current set up in it by all signals received by the antenna, but that the current set up by the wanted station the circuit is tuned to receive, is reduced greatest of all. If these facts are firmly grasped by the student, he should experience no trouble in quickly and thoroughly understanding all conditions met with in problems of sharpness of tuning and separation of the signals received from the various broadcasting stations.

In general, the degree to which a radio receiver is capable of differentiating between signals of different carrier frequencies, is a measure of its *selectivity*. A highly selective receiver (sharp tuning), has a tuning curve somewhat like that of A, and is able to so weaken the currents of the unwanted stations, and not weaken the current set up by the wanted station, that only the signals of the station to which it is tuned, are heard. In a receiver having poor selectivity (broad tuning) the ratio of the currents set up by the station to which it is tuned, to those of all other unwanted stations, is low, so several of them may be heard simultaneously, creating *interference*.

248. Two-circuit tuner: A consideration of the foregoing discussion on selectivity makes it at once apparent that the simple receiving system of (A) and (B) of Fig. 179 will not be very satisfactory, for the simple reason that the tuned circuit which consists of the aerial wire AB, the lead-in wire to the tuning coil, the tuning coil itself, the wire to the ground, the resistance of the contact to the ground (this resistance may be high if a poor ground connection or contact is employed), and the part of the ground through which the electrons surge back and forth, will have quite some resistance and therefore the tuning will be quite broad. The resistance of an antenna circuit depends of course on the lengths and size of wire employed, ground resistance etc., but in some ordinary receiving antennas the total resistance may be as high as 25 to 100 ohms or even more, depending on the care with which the wires are run, the joints and splices made, etc. (This is the high-frequency a-c resistance, which as we shall see later, is somewhat higher than the simple d-c ohmic resistance.) Resistance as high as this in a tuned circuit will reduce the current very much and the tuning will be broad, as shown by curves B and C at (D) of Fig. 179. In order to keep the antenna circuit resistance out of the tuned circuit, we may employ the arrangement shown at (A) of Fig. 180. Here, the tuning coil consists of a primary winding P

of a few turns of wire and a secondary winding S, usually having more turns. The primary P is placed near the secondary, so that the fluctuating magnetic field set up by the flow through it of the antenna currents of various frequencies produced by the voltages set up in the antenna circuit by the passing fields of all transmitting stations, will link and unlink with, and induce corresponding voltages in the secondary winding S. We will now discard the previous method of varying the resonance frequency of the tuned circuit by means of a coil of variable inductance, and use the more practical and common one of employing a coil of fixed inductance together with a condenser of variable capacitance. The variable tuning condenser may be a single section of the form shown in Figs. 98 to 101, with a set of movable rotor plates which can be rotated in or out between a set

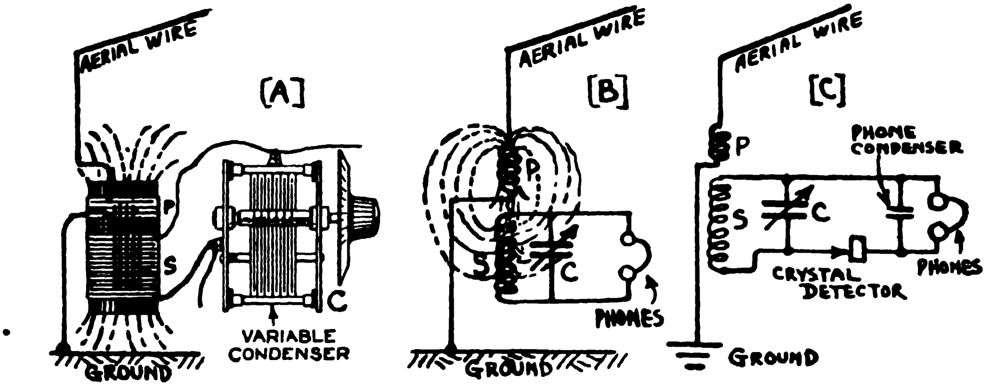


Fig. 180—Two circuit tuner arrangement. The need for, and connection of, the detector.

of fixed stator plates in order to vary the capacitance. For modern receivers in which single-control tuning is desired, this arrangement has been found to be mechanically and electrically superior to the variable-inductance arrangement.

Note: Variable inductances in the form of carefully designed tapped coils are used to a great extent in short wave receivers designed to cover a large range of transmitted frequencies, but are not used to any extent in ordinary broadcast band receivers. Commercial receivers of this type have a tuning range from 15 to 650 meters (about 20,000,000 cycles to 460,000 cycles). This range is obtained by means of special coil-switching arrangements which will be described in Arts. 557 and 563 of the Chapter on Short Wave Reception.

The tuning coil or transformer employed for the arrangement of Fig. 180 is of the air-core type, because an iron-core transformer in this position would have considerable losses due to hysteresis and eddy currents set up in the iron core by the rapidly alternating magnetic flux, which alternates as many as 1,500,000 times a second if the signal from a station transmitting on say 200 meters is being received. For these reasons, *radio-frequency* transformers of this type are almost always of the air-

core form shown at (B) of Fig. 75, and elsewhere throughout this book. It is evident that the magnetic coupling between the primary and secondary windings can be varied between wide limits by using more or less turns on the primary coil and placing them closer or further away from the secondary. The ratio between the induced voltage in the secondary and the voltage applied to the primary in an air-core transformer is not equal to the ratio of the number of turns as in the case of an iron-core transformer, but depends on the closeness of the magnetic coupling between the primary and secondary since all of the lines of force of the primary may not link with the secondary. For some constructions and conditions of coupling, the secondary voltage may even be less than the primary voltage, even though the secondary has more turns than the primary.

The number of turns of wire used on the secondary winding is fixed by the capacitance of the particular tuning condenser to be used and the frequency range it is desired to be able to tune to.

It would seem advisable to use a large number of turns on the secondary winding in order to make the voltage induced in it as large as possible. If this is done, the inductance of the secondary winding becomes large and since the resonant frequency is equal to $f = \frac{159{,}000}{\sqrt{LC}}$ it is evident that if the circuit is to be designed to tune up to a given maximum frequency, the larger the value of inductance used, the smaller the value of tuning capacitance required. Thus, if the number of turns on the secondary is increased, the size of the tuning condenser must be decreased. However, we do not gain as much as we might think by using a large number of turns on the secondary, for as we increase the number of turns we use more wire and so increase the resistance of the coil. This resistance tends to reduce the current flowing in the tuned circuit and so reduces the voltage appearing across the coil and condenser, thereby tending to offset the advantage gained by more secondary turns. For broadcast band work, a satisfactory compromise between these factors has been obtained by employing variable tuning condensers having a maximum capacitance value of .00035, .000365 or .000375 microfarads and a secondary winding having the proper value of inductance to tune to 550 k.c. or 545 meters (the upper limit of the broadcast band) with this value of capacitance. The use of .00035, .000365 or .000375 mfd. tuning condensers has almost become standard for this purpose in the United States. For short wave work, it is common to use condensers having a maximum capacitance of about .00015 mfd., with suitable tuning coils to cover the frequency ranges required.

Problem: A tuning condenser having a maximum capacitance of .00035 microfarads is to be used in a radio receiver to tune the secondary winding of an r-f transformer up to 545 meters (550 k.c.) the upper limit of the broadcast band. What must be the inductance of the secondary winding of the tuning coil it is connected to?

Solution: Since $f = \frac{159{,}000}{\sqrt{LC}}$, we may solve this equation for L by squaring both sides, and then setting L alone. When this is done, we have

$L = \frac{159{,}000^2}{f^2\,C}$. Substituting the values in the above problem in this equation, we have

$$L = \frac{159{,}000 \times 159{,}000}{550{,}000 \times 550{,}000 \times .00035} = 240 \text{ microhenries. Ans.}$$

The primary winding P, in the antenna circuit usually contains only a few turns of wire, so its inductance is small. Therefore, under this condition, the main antenna circuit will be rather broadly tuned because the resistance of the antenna circuit is relatively large compared with its total inductance and capacitance. Since its tuning is then very broad (as represented by curve C in (D) of Fig. 179), it does not exhibit any marked resonance properties and equal signal voltages of all frequencies induced in the antenna circuit, will cause equal currents to flow in this circuit. The antenna circuit is therefore said to be *aperiodic;* that is, without any definite period or frequency. It is true that the signal of the wanted station could be strengthened somewhat by tuning the antenna circuit to its frequency thereby strengthening its current, but as we have already seen, the resistance of the usual receiving antenna circuit is so high and the tuning therefore so broad, that most set designers have felt that not enough is gained by tuning it to make the cost of the extra tuning condenser and the need for manipulating it worth while. They have preferred to make up for this loss of signal strength by using more amplification in the vacuum tube amplifier employed. Therefore most of the radio receivers designed for home use have an aperiodic antenna circuit.

249. Gain produced by tuned circuit: At this point, we have reached the stage in our progressive design of a satisfactory radio receiving system where we have succeeded in making the passing electric fields of all transmitting stations induce voltages in an antenna system. These voltages produce a flow of rapidly alternating currents in the antenna circuit. By means of the r-f transformer shown at (A) of Fig. 180 we succeeded in transferring some of the energy by transformer action from the antenna circuit into the secondary circuit by means of the magnetic field between the primary and secondary coils. Then by means of a variable tuning condenser C, we formed a series resonant circuit, and utilized the principle of series resonance to present a very low impedance path in the tuned circuit to currents of the frequency of the wanted station, and a much higher impedance to the flow of currents of all other frequencies from all other stations. Therefore that voltage induced in the secondary winding which has the frequency of the wanted station for which the circuit is tuned, will set up a relatively large current in the tuned circuit. The voltage drop appearing across both the secondary S, and the tuning condenser C under this condition, will be greater than the voltage induced into the secondary winding by the electromagnetic induction from the primary; that is, the tuned circuit itself causes a "gain" of voltage.

The student is referred to article 174 for the detailed discussion of how a "gain" in voltage is produced by a tuned circuit considered alone. The gain is numerically equal to $\frac{2\pi f L}{R}$ where f is the frequency of resonance in cycles per second, L is the inductance in henries and R is the total high-frequency resistance of the tuned circuit in ohms. The expression $\frac{2\pi f L}{R}$ is sometimes referred to as the *figure of*

merit of a tuning coil. Since the resistance of modern tuning condensers and that of the wires connecting the coil to the condenser is so low as to be neglected for practical purposes, the entire resistance of the tuned circuit is considered as being in the coil alone. Since $2 \pi f L$ is really the inductive reactance of the coil, it is evident that the higher the inductance of the tuning coil used, the greater will be its inductive reactance and hence it would seem that the gain would also be higher. This advantage of using a high-inductance tuning coil is partly offset by the fact that as the turns are increased in order to increase the inductance, the resistance will also increase (sometimes very rapidly, depending on the physical form of the coil) and as the resistance forms the denominator of the expression for gain, it would tend to reduce the gain actually obtained. Therefore, the ratio of the inductive reactance to the resistance of the coil must be considered as a measure of its efficiency in this respect.

The result of the voltage gain resulting from the use of the tuned circuit, is that a higher voltage appears across the coil and condenser in the tuned circuit at the frequency of resonance, than would otherwise exist across them as a result of the simple transformer action from the primary. This of course is a very worthwhile advantage resulting from tuning the receiving circuit.

250. Changing the electrical energy to sound: Up to this point, we have concerned ourselves merely with building up the received signal voltage and current from the wanted station as much as possible with the simple devices at hand, and opposing and weakening the current from all unwanted stations. The voltage impulses appearing across the tuning coil and condenser will be quite strong when the circuit is tuned exactly in resonance with the signal of the station being received. Since our ears do not respond to electric currents or voltages, the problem now is to convert these voltages back into sound waves exactly similar to those originating in the transmitting stations. The ordinary telephone receiver will perform this function, for in the telephone system it is used to change the variations in electric current transmitted over a telephone line, into corresponding variations in air pressure (sound waves), at the receiver. The same type of instrument, modified somewhat in construction and form in order to make it light in weight and more practical for the conditions encountered, can be used for radio telephone reception. It is commonly known by the various popular names of *earphones*, headset, phones, receivers, watch-case receiver, etc. Where a comparitively large amount of electrical energy is to be converted into sound, we use a larger instrument known as a *loud speaker*. The principles of operation of loud speakers are somewhat similar to those employed in earphones but they will be studied later. Let us now see how the ordinary earphone is constructed, and operates.

Earphones, like the ordinary telephone receiver, operate on the electro-magnetic principle. However, since the energy received by the antenna of a radio receiving station is very feeble, and therefore the energy available to operate the earphones in order to produce the sound is very small (we are not considering the case of radio receivers using vacuum tube amplifiers for increasing the signal energy as yet) earphones must be constructed to be much more sensitive than the ordinary telephone receiver for which stronger currents are available in the wired telephone line.

Earphones usually consist of two separate earpieces connected in series and held to the ears by a metal headband as shown in Fig. 181. Each earpiece has a metal or hard rubber cup D, with a hard rubber cap G. In the bottom of the cup is a strong permanent horseshoe magnet E, with pole pieces F. Around each pole piece, a coil

H, of many thousands of turns of fine insulated wire (No. 40 to 50) is wound. The magnetic field produced by the signal current flowing through these coils either aids or opposes the steady field of the permanent magnet, depending on which direction the current flows through them.

The two coils are connected in series, so the current passes through both windings. Sensitive headsets have several thousand turns of wire on the coils, so that even very feeble currents flowing through them produce an appreciable change in the magnetic field of the permanent magnet. Suspended above the pole pieces, and very close to them, is a thin, flexible, soft-iron diaphragm about .001 inch thick. A commercial set of earphones with headband is shown at the right of Fig. 181. The phone on the right has been opened to show the screw cap (center), and the diaphragm (right).

251. Earphone operation: The operation of each unit of an earphone of the type described above is as follows:

When no current flows through the coil, the magnetism of the permanent magnet attracts the iron diaphragm and bends it slightly, as shown by position A in Fig. 181,

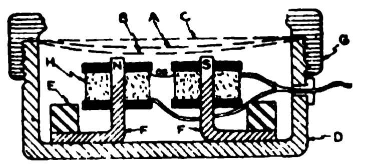


Fig 181—(Left): Cross-section view of an earphone unit showing the permanent magnet, magnet coil and diaphragm

(Right): A pair of standard earphones with headband The two units are supplied with a 5-foot cord with phone-tips for connections

producing an initial deflection. Assume the left-hand pole piece to be a north pole and the right-hand one a south pole. If one complete wave of an alternating current is flowing through the receiver, so that the current during the first half of the wave flows through the coils in such a direction as to produce magnet poles similar to those of the permanent magnet, then this magnetism adds to that of the permanent magnet and the field is strengthened. This increases the attraction on the diaphragm and pulls it down further, to point B. On the next half wave, the direction of the current reverses, and so the magnetic field produced by its flow through the coils also reverses, and opposes that of the permanent magnet. The resultant field is now weaker than that of the magnet alone, so the diaphragm springs back to position C. At the end of the cycle it goes back to A. Therefore, during one cycle it makes a complete vibration from A to B to C, the *amplitude* of the vibration depending on the *amount of variation of current* flowing through the coils. This rapid back-and-forth movement of the diaphragm sets the air in motion and creates sound waves that travel out through the opening in the cap. If the frequency of the current sent through the winding lies within the audible range (about 16 to 20,000 cycles per second), the sound waves produced by the corresponding movements of the diaphragm also being of the same frequency, will be heard by the human ear. Thus the earphones can be used to change *variations* in an electric current or voltage applied to them, into corresponding *variations* in air presure—or sound waves. It must be remembered that it is the amount or *degree of variation* of the current through the coils that produces the motion of the diaphragm and the sound, and not merely the total number of amperes

or milliamperes of current sent through. Unless the current *varies*, there is no *change* of magnetic pull on the diaphragm and hence no sound is produced. If we sent an absolutely steady current through the windings, the magnetic field produced when the current started flowing, would cause a single change in position of the diaphragm and we would hear a "click". The diaphragm would stay in that one deflected position as long as this steady current flows through; and absolutely no sound would be produced, simply because there is no motion of the diaphragm. If the coils could carry it, we could send 1,000 amperes of steady direct current through a pair of earphones or a loud speaker without producing the slightest sound from it! This should be remembered, for as we shall see later, we design radio receiving equipment to produce the maximum signal current or voltage variations. These in turn produce the maximum amplitude of vibrations of the loud speaker diaphragm and hence maximum loudness or intensity of sound.

252. Need for the detector: Now that we have a device capable of converting variations in electric currents or voltages into sound waves, it would seem that our receiving equipment is complete. We might expect that we could simply connect a pair of earphones across the coil and condenser of our tuning circuit, (across which the maximum varying signal voltages appear due to the "gain" of the tuned circuit), as shown at (B) of Fig. 180. Unfortunately, if we did this we would not hear a single sound! In order to understand why this is so, we must go back to our broadcasting station. It will be remembered that in order to successfully accomplish the radio transmission of sound programs, we varied or "modulated" the strength of the individual cycles of the radio-frequency carrier current in accordance with the sounds transmitted, as shown in Fig. 172A. For instance, for the transmission of sound of "a" as in father, the high-frequency alternating current flowing in the antenna circuit of the transmitting station would look like that at (A) in Fig. 182 and at the right of Fig. 172A. Let us see what happens when this is received by our receiver. The currents set up in any receiving antenna by the radiated wave of this station would be exactly the same as this. only much weaker in strength of course. The current flowing in the tuned circuit of the receiver, and therefore the voltage variations appearing across the terminals of the coil or condenser at (B) of Fig. 180, would also vary exactly the same. Consequently we are applying to the terminals of our earphones a high-frequency (radio frequency) alternating voltage, each cycle fluctuating in value in exact accordance with the sound variations shown in Figs. 172A and 182. For transmitting stations in the broadcast band, the frequency may be anywhere from 550,000 cycles to 1,500,000 cycles per second depending on the particular station being received. What happens? The answer is,—nothing! We shall now see why:

First, the magnet coils of the earphones, (or loud speaker) having a necessarily large inductance due to the fact that they consist of a great number of turns of wire wound on the iron core, offer a very high impedance or opposition to the flow of signal currents of such high frequency through them, and will not allow them to flow through. A set of earphones having a direct current ohmic resistance of 2,000 ohms may have an impedance of four or five thousand ohms at a frequency of only 1,000 cycles. Remembering that the impedance of an inductor varies directly as the frequency is increased, we can imagine what impedance they would present to the flow of the received r-f currents of 550,000 cycles or higher.

Second, even if some of the high-frequency current did flow through the earphone coils, and the diaphragm made a complete vibration for each individual cycle, it would be vibrating so rapidly that the ear would not respond to it, for the highest frequency

sound that the human ear can hear is around 20,000 vibrations per second. Actually it is impossible for any diaphragm which has some inertia due to its mass, and which is not perfectly flexible, to vibrate as fast as this current would tend to make it move. It is evident from these considerations that the circuit shown at (B) of Fig. 180 is impractical.

Let us see what is to be done. Referring back to Fig. 171 it is evident that B represents the original sound pressure variations. Therefore we want the diaphragm of our earphones or loud-speaker to move in accordance with these variations. Now refer to curve D. This is the form of the modulated high-frequency carrier current. Our sound wave-form is now represented by the dotted line wave connecting the peak values of the individual *half cycles of current in one direction*—which one does not matter—it may be either the negative half-cycles or only the positive ones. Now refer to (A) of Fig. 182 which represents the high-frequency alternating current or voltage variations existing in the tuned circuit of the receiver. It is evident that we do not want the diaphragm of our earphones or loud speaker to follow the variations in current of each individual cycle of this a-c for this is not the wave-form of the sound. What it must do in order to faithfully reproduce the sound wave of A in Fig. 171 is to merely follow the *variation in the maximum or peak values of the current or voltage in one direction only,* that is, it must move according to the dotted envelope curve drawn through the peak values of the individual half cycles in one direction as shown. It is evident that to do this, it is first necessary to make the current alternations in only one direction effective, so the current flows through the earphones in one direction only. This may be accomplished by means of a rectifier of some kind, that is, a device which allows current to flow easily through it in one direction only, and offers a very high resistance to the flow of current through it in the opposite direction.

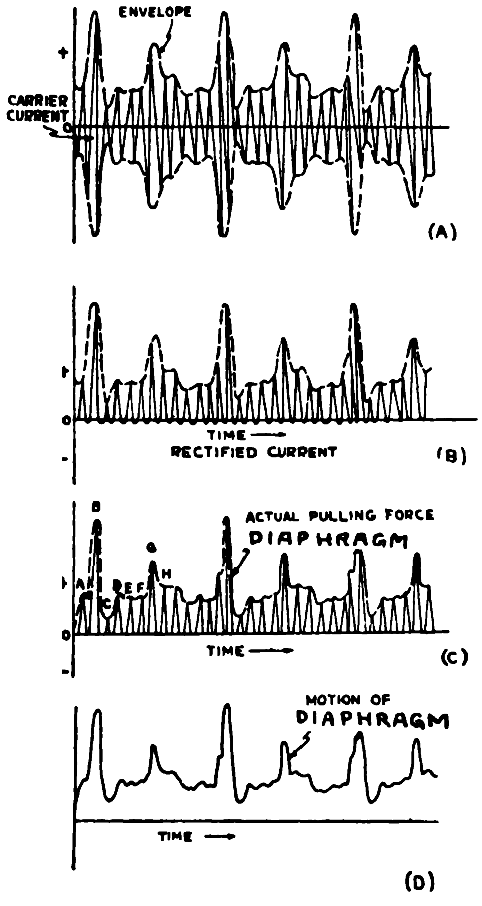


Fig. 182:—(A) Wave-form of received current for message of "a" as in "father." (B) Current rectified by detector. (C) Pulling forces on the earphone diaphragm. (D) Final motion of diaphragm and sound wave produced.

253. The crystal detector: A vacuum tube connected as a detector is used for this purpose in modern receivers, but for our purpose in developing a simple receiving system we may use the common *crystal detector* in series with the earphones as shown at (C) of Fig. 180 to perform the function of rectification or detection. The construction and operation of this is as follows:

The crystal detector usually consists of a very fine wire called a catwhisker, arranged to make light contact with a crystal of some particular material such as galena (lead sulphide) held in a cup by a metal alloy of low melting point as shown at the left of Fig. 183. Other mineral combinations such as iron pyrites, carborundum, silicon, molybdenite, etc. can be used, but for our purpose of explanation, the simple galena detector will suffice.

When an alternating voltage is applied to the combination, it tends to make current flow from the catwhisker to the crystal during the first half cycle. The resistance which the crystal and contact offer to current flow in this direction is low, so the current is able to flow through easily. On the next half cycle, the voltage is reversed and tends to send current in the opposite direction. The detector contact offers a very high resistance to current flow in this direction, so very little current is allowed through. The action is repeated for each cycle. This is shown graphically in (A) and (B) of Fig. 182. At (A) we have the modulated high-frequency varying voltage impressed across the detector and phone circuit by the tuned circuit. At (B) we have the half wave rectified current which gets through the crystal rectifier and earphones. Notice that this is still a varying high-frequency current, but it now flows only in one direction since one half of each cycle of current flow has been eliminated. A very small amount of current does get through the detector in the opposite direction, as shown at (B) by the small loops below the axis line. It is the difference in strength of these two currents which determine how well or how poorly the crystal operates as a detector. A good crystal will almost entirely eliminate the flow of current in one direction.

254. Detector action: It would seem that the pulses or fluctuations of current flowing through the rectifier and earphones as shown at (B) of Fig. 182 are still much too rapid to actuate the diaphragm, since their frequency is now half that of the carrier current (the current flow during half of each cycle has been eliminated). Their effect on the receiver diaphragm however, is for each wave-train to give force by successive addition, as can be seen from the following:

The first impulse "A", shown in part (C), passes through the earphone coils and produces a slight movement of the diaphragm. If the station is transmitting at say 200 meters, corresponding to a frequency of 1,500,000 cycles per second, then the time interval between two successive maximum values of current, as A and B, is one one-million five hundred thousandth part of a second. Obviously, since the diaphragm has inertia and stiffness, it is somewhat sluggish in action and cannot possibly make a complete vibration in this time, so the second impulse B will occur before the diaphragm has had time to spring back in place, and will therefore deflect it further. The next impulses C, is a weak one and the diaphragm will therefore spring back a bit. Impulse D, is stronger and causes the diaphragm to move outward again, etc. The result is, that the diaphragm does not move from its zero or initial position out to some other position and back for every half cycle of the high frequency current but instead, is deflected slightly in or out from its mean position by each pulse of current and therefore its motion follows more or less faithfully, the shape of the envelope wave of this current, as shown by the dotted lines at (C). This movement is shown at (D) for clearness. By referring back to (B) of Fig. 171, and to Fig. 172A, it will be seen that the movement of the diaphragm and consequently the sound waves it produces are exactly the same as the original sound wave in the transmitting station. The volume, and frequently the quality, of the sound in the phones is improved by connecting a small fixed condenser of about .0005 mfd. capacity across them, as shown in the circuit at (C) of Fig. 180.

The operation is then as follows: During the duration of one impulse A of the rectified current of (B) and (C) of Fig. 182, the current flows through the earphone coils and also charges this condenser. During the next half cycle no current flows through the detector. At this instant, the phone condenser being connected across the phone coils, and having an electric charge on it, partially discharges through them. The discharge current of the condenser is in the same direction as that of the impulse A. This acts to keep the diaphragm in position until the next impulse B comes along. The current flowing in the telephone receiver is then like that shown in the somewhat enlarged and exaggerated dotted line in (C). There is, then, during each wave-train a more continuous attraction on the earphone diaphragm, with resulting improved reproduction, since the diaphragm follows more nearly the outside curve or envelope of the current.

In earphones and loud speakers there is some capacity existing between the individual turns of wire on the coils, and the usual five-foot external connection leads supplied with earphones being close together, also form a condenser. This combined

capacity is usually enough to give the above action, so that no additional phone condenser is necessary. In diagrams in future chapters the condenser will be omitted, although the reader should remember that a capacity really does exist there.

In this way, by the aid of a receiving antenna system, electrical resonance, a rectifier or detector, and a device for changing variations in an electric current into corresponding sound waves, we are able to successfully receive the electrical impulses sent out by radio transmitting stations, select the current of the station we want to hear, rectify this to pulsating direct current, and finally convert it back to sound waves similar to those of the original program, and which can be heard by the listener.

The crystal detector is sometimes called a *square law* detector since the current flowing through it varies as the square of the applied voltage.

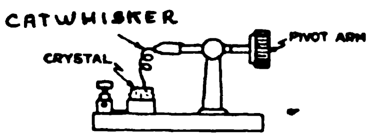
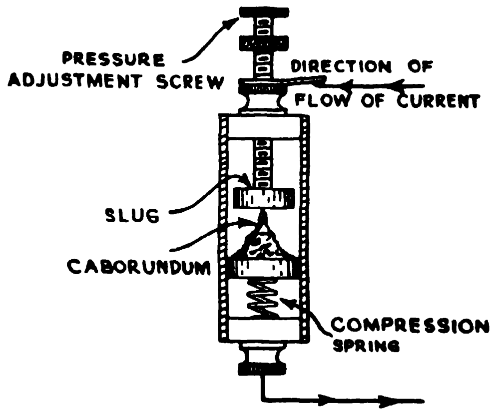


Fig 183—Left: A simple crystal detector with a light catwhisker resting against a galena crystal
Right: A modern semi-adjustable carborundum crystal detector with the crystal and contact slug held together under pressure



Thus if twice the signal voltage is applied to it, the current flowing through it will be four times as much. Evidently such a device does not follow Ohm's law, because its resistance is not constant but varies with the applied voltage.

255. The carborundum crystal detector: The carborundum crystal detector has become popular as a rectifier in simple receivers due to its very stable operating characteristics. A commercial form of carborundum crystal detector cut open to show its parts is shown at the right of Fig. 183. Its construction and operation is as follows:

A crystal of carborundum is held in contact with a slug of metal under a pressure of about five pounds by a compression spring. The pressure may be regulated for best operation by the pressure adjusting screw which comes out at one end. The entire unit is enclosed in an insulated protective casing. This combination offers a very low resistance to the flow of current from slug to crystal, but presents a very high resistance to current flow from crystal to slug, thus acting as a detector or "rectifier"

Fig. 184 shows two practical circuits for a Carborundum detector. At A, the rectifier is placed across the entire tuned circuit. At B the rectifier is placed across only a portion of the circuit. The arrangement in B is preferable as it gives much better selectivity with very little loss in efficiency, when the tap is properly located.

256. Constructing a crystal receiver: A very cheap and efficient crystal set for earphone reception can be constructed from the circuit diagram of Fig. 185. A set of this kind is very useful as a preliminary receiver with which to learn the characteristics of tuning circuits in radio receivers, and is also a very good project for radio set construction before advancing to more involved and complicated vacuum tube receivers.

The primary coil P consists of a total of 32 turns of No. 28 B. and S. gauge double silk or cotton covered copper wire wound in a single layer on a tube four inches long and two inches in outside diameter. The coil is tapped at 2, 4, 8 and 16 turns. In winding the coil, twists should be made for each turn from which taps are made,

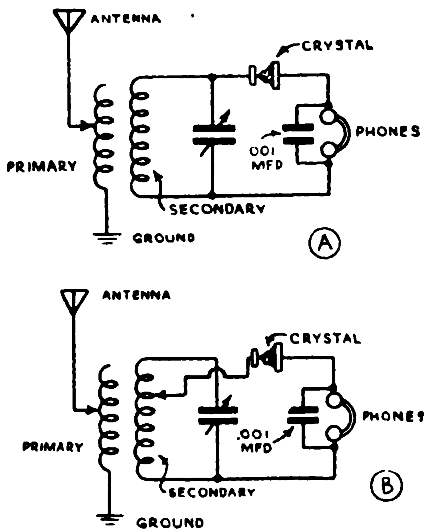


Fig. 184—Two carborundum crystal detector receiving circuits.

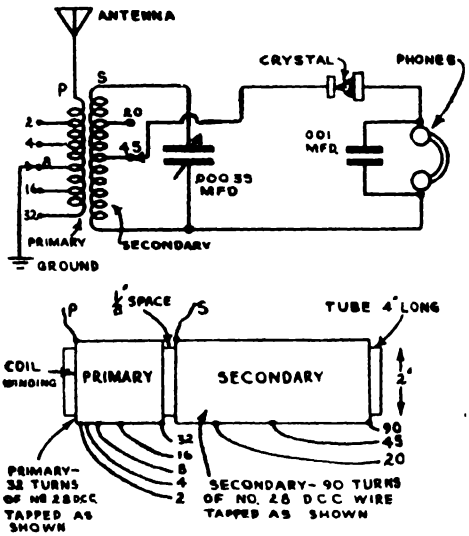


Fig. 185—A practical radio receiver with crystal detector (see lower left of Fig. 187)

so as to make connections to the taps easy. The secondary coil consists of 90 turns of No. 28 D.C.C. wire wound in a single layer on the tube next to the primary and separated from it by ⅛ inch. A tap is made at the 20th and 45th turn. The tap which gives best volume consistent with good selectivity should be used. An aerial from 75 to 100 feet long should be employed. Tuning is accomplished by the .00035 mfd. capacity variable condenser. The phones are by-passed by a .001 mfd. fixed condenser. A complete receiver of this kind is shown in the photograph at the lower left of Fig. 187. The layout of the various parts is shown. The Carborundum crystal should be connected as shown. Adjustment for best selectivity can be made by operating the set with the ground connected to the various taps of the primary coil in turn, until the best operating point is found.

257. Operation of the entire receiver: An idea of the various changes which take place in our simple crystal receiver may be gained from a study of Fig. 186. At the left, the weak modulated r-f signal is induced in the antenna circuit. Of course many signals of differert frequencies are induced here by the various stations, but these are not shown here as they would confuse the diagram. Then this r-f voltage is

strengthened by the gain of the tuned circuit, then the current is rectified by the crystal detector; the rectified current sent through the earphone coils produces vibration of the diaphragm in accordance with the peak values of the individual pulsations and produces the sound waves which are practically an exact duplicate of those originating in the broadcasting station.

258. Measuring crystal detector characteristics: The operating characteristics of crystal detectors or rectifiers can be determined very easily by the arrangement shown at (A) of Fig. 187.

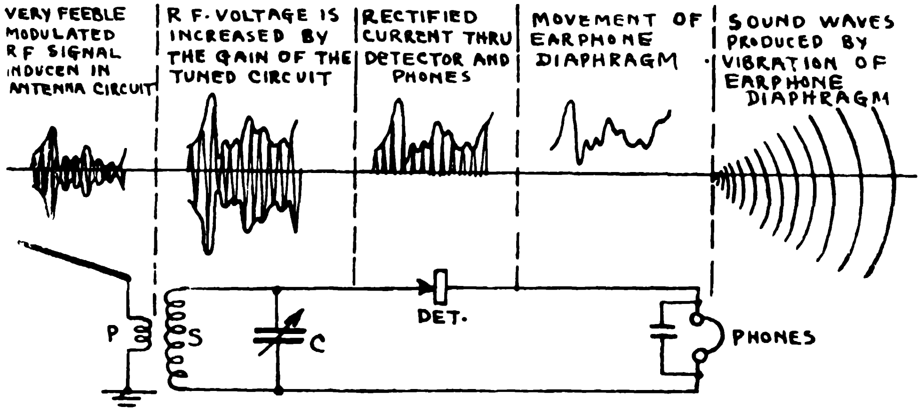


Fig 186—Analysis of the changes which the received electrical energy undergoes in the various parts of a simple crystal-detector radio receiver

The source of e.m.f. is a single dry cell. The voltmeter is a good low reading instrument sufficient to register the voltage of the battery. The milliammeter has a range of 0 to 1 milliampere. The 200 ohm potentiometer P is used to apply any definite voltage to the crystal. The milliammeter measures the current which the crystal allows to flow. The reversing switch S is used to apply either a positive or negative potential to the detector. The potentiometer is set for voltage steps of 0.1 volt and the corresponding currents are read on the milliammeter. This is done for both positive and negative voltages.

At (B), a graph of current flow plotted against applied voltage is shown for the carborundum crystal detector of Fig. 183. Curve O-B represents the current flow when e.m.f. is applied in the positive direction (slug to crystal). Curve O-C represents the current flow when e.m.f. is applied in the negative direction (crystal to slug). Notice that practically no current flows through the crystal in this direction (unless the applied voltage is made quite high). This illustrates the rectifying properties of this crystal arrangement.

Most crystal detectors can be roughly checked for rectification by connecting a dry cell (1½ volt), pair of phones and the detector in series. A strong click should be heard when the detector is connected in one direction, and almost no click when reversed. This indicates that the detector rectifies properly.

259. Limitations of crystal receivers: The simple receiver circuits discussed thus far, furnish a system of radio reception by which sound programs can be heard, and in which the volume of sound produced depends *entirely* on the strength of the electric fields acting on the receiving antenna. The energy of the ordinary transmitter is radiated out in all directions around the transmitting antenna. Owing to the com-

paritively small size of the receiving antenna, the latter can cover only an extremely small part of the large area over which this energy is spread, so that the energy actually imparted to any receiving antenna is very very small, and the voltages and currents induced in the antenna circuit are very feeble. It is evident that simple crystal detector radio receivers of the type just described cannot be used for long distance reception, be-

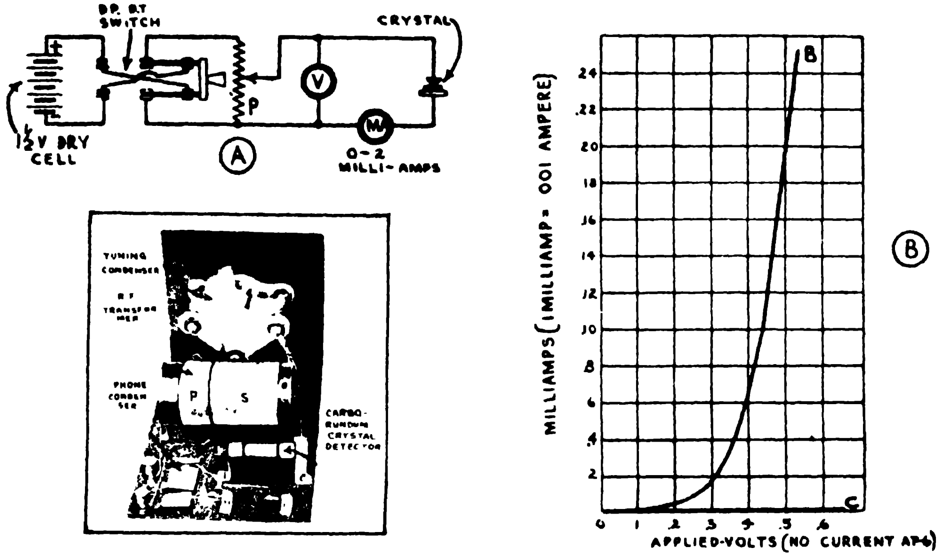


Fig. 187—(A): Rectifier test circuit which may be employed to test the rectifying properties of a rectifier. (B) Rectification characteristics of a carborundum rectifier. (Lower left): The complete crystal-detector radio receiver whose circuit diagram is shown in Fig. 185.

cause the received currents will not be strong enough to operate the ear- phones.

The use of earphones is unpopular, as people desire to hear the sound programs in comfort with loud speakers which produce enough volume to fill good sized rooms. Loud speakers require a stronger operating current than do ordinary earphones since they set a greater volume of air in motion and produce larger amplitudes of sound vibrations, so amplifiers have been developed to amplify the received radio voltages to make loud speaker operation possible. These employ vacuum tubes in their operation. The crystal detector, while producing remarkable clarity of reception, is unable to handle either very weak or very strong impulses of current satisfactorily and simple crystal receiver circuits do not pass enough energy on to a loud speaker to operate it satisfactorily. To be able to listen to distant stations and operate a loud speaker we must strengthen or amplify the incoming signal voltages.

Crystal detectors have been superseded almost entirely by vacuum tube detectors, due to their greater sensitivity, ease of adjustment, and property of not only rectifying, but also amplifying at the same time.

The rectifying ability of a crystal is an inherent property of the crystal and cannot usually be altered or improved. The point of best selectivity must be determined by trial by moving the catwhisker over the surface of the crystal. In most cases, this point is never located. The adjustment is not permanent, and heavy currents such as those received from powerful nearby broadcasting stations may make the detector inoperative by setting up a comparatively great amount of heat at the contact point, thus oxidizing the catwhisker and destroying the conducting properties. The use of the Carborundum crystal detector eliminates the adjustment difficulties but does not satisfy the amplification requirements for loud speaker operation. Some receivers have been devised to use a carborundum crystal with radio and audio frequency amplifiers employing vacuum tubes. Such *hybrid* receivers are capable of very fine performance if correctly designed but their use is not very widespread.

The use of vacuum tubes makes it possible not only to perform the function of detection or rectification, but also to build up the strength of the feeble voltage impulses induced in the antenna circuit to practically any degree so that one or more loud speakers may be operated with ample volume to fill a room or an auditorium with sound. We will now study the theory of operation, and construction of the various types of vacuum tubes employed in modern radio equipment and later we will study the various circuits in which they are employed.

REVIEW QUESTIONS

1. What is the approximate frequency range of the sound vibrations in (a) speech, (b) music?
2. What is the approximate frequency range of the carrier currents used in radio broadcasting stations in the band between 200 and 550 meters?
3. What sets up the voltages and current in the antenna circuit of a radio receiving station? Explain the action in detail.
4. Station WEAF in New York City transmits with a power of 50,000 watts, radiating it out into space in all directions. Why does the amount of signal power picked up from this station's field by a receiving antenna amount to only a few microwatts?
5. What is the purpose of (a) the receiving antenna; (b) the connection to the earth or "ground"?
6. What is a counterpoise ground, and why is it used? Draw a diagram showing an ordinary aerial and counterpoise ground connected to a radio receiving set.
7. What is the receiving antenna made up of? Would copper wire having an outer covering of ordinary insulation be satisfactory? Why?
8. Explain how the antenna, lead-in wire, ground wire, and ground form a condenser.
9. What would be the effect on the total antenna circuit capacitance, of connecting a small fixed condenser in series with the lead-in wire? What is the effect of connecting a small condenser between the antenna and ground? Explain!

10. Explain with diagrams, how current is able to flow in the wire circuit between a receiving antenna and ground, when apparently this is an open circuit.
11. Show by diagrams and explain, the difference between a "tuned" and an "untuned" antenna circuit.
12. What is an aperiodic antenna circuit? What are its advantages and disadvantages?
13. What is meant by "tuning" a radio receiver and how may it be accomplished? Why is tuning necessary? State two benefits received from tuning a radio receiving circuit.
14. Under what conditions of inductance and capacitance value is the tuned circuit in a radio receiving circuit said to be in resonance with, or tuned to, the frequency of the incoming signal impulses of the station it is desired to receive?
15. What value of capacitance is required with a 200 microhenry coil to form a tuned circuit resonant at 600 meters?
16. Explain how a voltage gain is obtained by means of a series tuned circuit.
17. Explain two objectionable effects caused by excessive resistance in a tuned circuit.
18. Why are the transformers used in the radio-frequency circuits of radio equipment usually constructed in air-core form?
19. What is meant by the process of "detection" and why is it necessary in a radio telephone receiver?
20. What function does the crystal detector perform in a simple crystal type radio receiving set? What is the function of the earphones or loud speaker?
21. What is the purpose of (a) the permanent magnet; (b) the coils, (c) the diaphragm, of an earphone? How are the current impulses changed into sound waves?
22. Explain why crystal detectors are not used in receivers which are to operate loud-speakers.
23. What is induced first in a receiving antenna by the action of the passing fields, voltage or current?
24. How does the action in a resonant tuning circuit make it possible for you to hear the signals from one station, and make all others so weak that they are not heard?
25. What electrical devices are necessary to form a tuned circuit?
26. Show by a circuit diagram, the connections of the following parts to be used in a simple crystal detector receiving set, radio frequency transformer, variable tuning condenser, crystal detector, earphones, earphone condenser, antenna, ground. Explain the operation briefly, starting at the antenna and following through to the earphones.
27. Explain the action of the phone condenser of small capacitance connected across the earphones or loud speaker of a receiver.

CHAPTER 17.

ELEMENTARY STUDY OF THE VACUUM TUBE

IMPORTANCE OF VACUUM TUBES — OUTLINE OF STUDY OF THE VACUUM TUBE THE EDISON-EFFECT — ELECTRONIC EMISSION FROM SOLIDS — PRODUCING ELECTRON EMISSION FROM SOLIDS — PRODUCING ELECTRON EMISSION BY HEATING — PRODUCING ELECTRON EMISSION BY LIGHT — ELECTRON EMISSION BY ELECTRON BOMBARDMENT — ELECTRONS FROM GASES — IONIZATION — CHOICE OF ELECTRON EMITTER — TWO-ELECTRODE VACUUM TUBE — SATURATION CURRENT — SPACE CHARGE AND SCREEN GRID TUBE — TWO ELECTRODE RECTIFIER — THREE ELECTRODE TUBE — AMPLIFYING PROPERTY — TUBE CHARACTERISTIC CURVE — TYPES OF TUBES — REVIEW QUESTIONS.

260. Importance of the vacuum tube: The basic idea of the thermionic vacuum tube has probably been the most important single invention in the development of the radio art, for without it, the high power—high quality radio transmission and reception we are all accustomed to today, would be impossible. It is used in radio transmitting stations for amplifying the speech currents set up in the microphone circuit; and for generating and modulating the high frequency carrier current which produces the electromagnetic radiations from the antenna. In modern radio-telephone receivers, vacuum tubes are employed for greatly amplifying and rectifying the weak signal voltages set up in the receiving antenna, in order to make loud speaker operation possible. They are also employed for rectifying the a-c current supplied by the a-c electric light circuits for the operation of radio receivers. The transmission and reception of television signals also depends entirely upon their use to perform these functions.

Hundreds of new applications are daily being found for various forms of vacuum tubes and their associated circuits in all branches of industry outside of the field of radio. As we shall see when studying some of these uses in a later chapter, they are being employed for such functions as, amplification; rectification; detection of current or voltage impulses; operation of counting and sorting devices, alarms and signal systems; controlling large amounts of energy and machinery; measuring all sorts of quantities; converting electrical energy for high voltage transmission in d-c form; etc. There are seemingly an endless variety of uses for this marvel of metal, glass, insulation, and empty space, and any person who expects to associate himself with either the radio or electrical industry must be on intimate terms with at least the simple fundamental theory

upon which the vacuum tube operates. It will be to his advantage to know, in addition to this, the various forms employed in industry, together with the special circuits in which they are employed in commercial devices.

Many forms of vacuum tubes are constantly being developed to perform most suitably the particular tasks which they are intended for. Thus we hear the terms 2-electrode, 3-electrode, 4-electrode, 5-electrode, a-c, d-c, screen-grid, variable-mu, high-mu, pentode, power, rectifier, thyra-

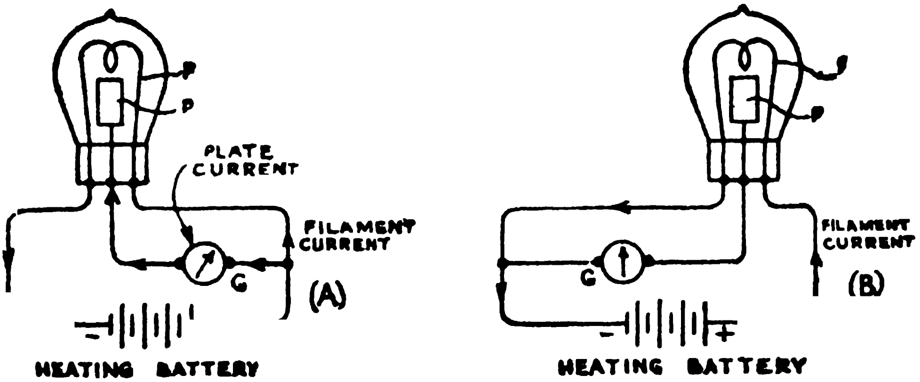


Fig. 188—The Edison-effect, which depends for its action, on the emission of electrons from an incandescent filament

tron, grid-glow, photo-electric, etc. applied to the various forms of vacuum tubes in use today. We will first study these simple principles of operation before passing on to a discussion of the various forms in which they are constructed and the special circuits in which they are employed.

261. Outline of study of the vacuum tube: To the student attempting a serious study of radio, or that of vacuum tubes, for the first time, the fact that there are so many types now made and used, must make it seem like an almost impossible task to try to understand the construction and operation of all of them. Fortunately, this is not so, for as we will now see, they all operate on the same fundamental principles. Once these principles are understood, the subject merely resolves itself into a systematic study of the particular mechanical construction features employed in the various types of tubes used, and the electrical characteristics which result from these special forms of construction. By pursuing the study in this way, the subject will be found to be not only very much simplified, but extremely interesting as well, for we will be dealing again with those fascinating little fellows, the "electrons". Since the emission and flow of electrons forms the basis of the operation of all electronic vacuum tubes, this phase of the subject will be studied first.

262. The Edison-effect: Almost fifty years ago (in 1883), Thomas A. Edison was at work on the development of the incandescent electric lamp which we now use for lighting purposes. Edison was troubled by frequent burnouts which occurred at the ends of the carbon fila-

ments he was using. Investigation disclosed that nearly all of the lamp failures occurred at the positive ends of the filaments. He constructed a special lamp in which he placed a metal plate terminal P, between the loop of filament wire, as shown in Fig. 188. The filament was heated by current from a battery or generator as shown. He found that when he connected the plate to the "positive" filament connecting wire, with a sensitive current indicating galvanometer in series, as shown at (A), a current flowed through the shunt circuit PFG thus formed, as indicated on the galvanometer. If the plate was connected to the "negative" filament connecting wire as shown at (B), no such current flowed, as shown by the fact that the galvanometer did not deflect. Furthermore, the direction of deflection of the galvanometer pointer in the former case showed that the current appeared to flow always from the *plate to the filament* when the plate was made positive, and never in the opposite direction. The current ceased as soon as the filament was allowed to become cold.

Here was a real mystery, for at that time nothing was known of the emission of electrons from hot bodies. A current was apparently flowing inside the tube, from the plate across the vacuum to the filament. A vacuum had always been thought of as a perfect electrical insulating medium because it contains nothing to conduct electricity. It is true, that a perfect vacuum without electrons in it, is a better insulator than any known substance; but at that time Edison did not know of course that there actually was something in between the plate and filament wire of his lamp. The action just described is now known as the "Edison Effect". Edison was too busy with the development of his lamp to spend much time investigating this effect at the time, but he made a record of it, and its causes remained a mystery until in 1899, J. J. Thompson showed that the phenomenon was due to electrons or particles of negative electricity given off by the filament when it was heated. The explanation now accepted in the light of our modern knowledge of electrons and the atomic structure of matter is based on the electron emission from solid bodies.

263. Electronic emission from solids: We have already studied in Articles 16 to 18, that every atom of any body is composed of one or more planetary electrons rotating around a central nucleus consisting of electrons and protons as shown in Fig. 17. We will now review this briefly:

Metals and other conducting substances are supposed to have many *free* electrons which are constantly wandering around, mostly through the comparatively large spaces between the atoms. If an e. m. f. is applied to a conducting material, a drift of these electrons takes place in a definite direction along the conductor, at a speed of about 300 to 125,000 miles per second depending on the intensity of the electric forces of the e. m. f applied, and we have what we commonly call *a flow of current*. Unfortunately, the actual direction of the movement or flow of the electrons is just opposite to that in which the resulting current is conventionally said to flow (see Article 25), since the rules regarding directions of currents through electric circuits were formulated arbitrarily before electrons were even thought of.

Under ordinary conditions of temperature, the electrons and atoms of a substance are in a constant state of motion and possess some energy

(kinetic energy) due to this motion. They do not escape from the substance, because according to a theory advanced by O. W. Richardson in 1901, there exists at the surface of the substance a force which tends to keep even the free electrons from escaping. (Of course the electrons in each atom are held to it by the force of attraction of the positively charged nucleus.) In order to escape from the surface of a substance, an electron must do work in overcoming the force which tends to hold it in the substance, just as a horse does work in attempting to draw away from a loaded wagon. This amount of work must be done at the expense of the kinetic energy of the electron. For all known substances, it would require far more energy than most of the electrons possess, for them to escape from the body at ordinary temperatures, so they are held within the substance and practically no electrons are emitted by the body. It is possible, however, to impart sufficient energy in some form to the electrons of many substances by some external means, so as to make them able to shoot out of (or be *emitted* from) the body. Of course, as soon as an electron is emitted, the unbalanced electrical force in the body tends to attract it back again, so that the final movement of the emitted electron depends upon what other external forces are acting on it at that time.

264. Producing electron emission by heating: It has been found that the forcible emission of electrons from a body (commonly called *electronic emission*) can be produced in several ways.

It is interesting to note that all of these methods involve imparting of electromagnetic radiations to the electrons of the body, in order to increase their kinetic energy enough to enable them to overcome the restraining forces. These forms of electromagnetic energy are heat, light, and moving electrons.

Probably the most common method is to heat the body in some manner, either by the application of a hot flame as shown at (A) of Fig. 189, by passing an electric current through it as shown at (B), or in any other way. It is interesting to note that heating by a gas flame was employed by De Forest in his original three-electrode vacuum tube. Heating by means of an electric current is now used exclusively, because of its convenience. In some vacuum tubes the electron emitter is heated by current from a battery, in others it may be heated by a-c or d-c current from the electric light circuit.

When the body is heated by any means, the electromagnetic radiations of energy, which really constitute what we call heat, go to the body and are given up to the electrons. This increases the speed of movement of the electrons and thereby increases their kinetic energy. As the imparting of the energy to the electrons is continued in this way by sufficient heating (raising the temperature of the body to a high enough value), some electrons will finally acquire enough kinetic energy to enable them to break away from the restraining forces, and shoot out from the body into space, that is, they are *emitted.* As the heating is continued, more and more of them acquire the necessary amount of energy needed to overcome the restraining forces, and they are emitted. The result is, that a

steady stream of electrons is obtained from the hot body as shown. The rate of emission of the electrons from a body is approximately proportional to the square of its temperature above that of red heat. It should be thoroughly understood that the heat for the emission can be supplied by any means we may want to use.

The emission of electrons from a heated body may be likened to the evaporation of water. If we raise the temperature of a vessel full of water by heating it, the

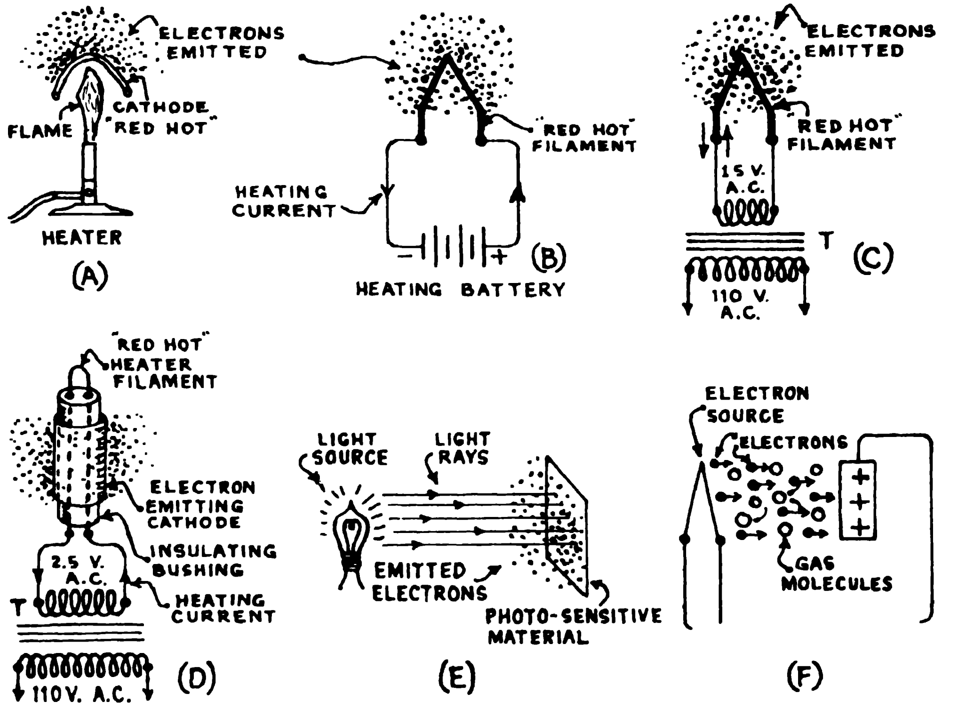


Fig 189—Various ways in which bodies may be made to emit electrons. (A) heating directly with a flame; (B), (C) heating directly with an electric current; (D) heating indirectly by means of electric current, (E) by photo-electric action of light; (F) by electron bombardment.

agitation of its molecules increases and when the temperature commonly known as the "boiling point" is reached, the molecules have gained enough kinetic energy to enable them to break through the surface tension of the liquid and shoot out into the atmosphere in the form of tiny particles of water vapor. Of course this action is not exactly like that of electron emission for in this case droplets of water, each containing many atoms and electrons are boiled off; in the case of electron emission only the tiny single free electrons are emitted.

Emission of electrons caused by applying heat to a body is called *thermionic* emission to distinguish it from emission produced in other ways. Devices in which this is made to take place are commonly called *thermionic* devices. The body which emits the electrons is generally called the *electron emitter* or the *cathode*. The body to which the emitted electrons may be attracted, is called the *plate* or *anode*. These terms should

be remembered. In almost all practical *thermionic* devices, the heating of the electron emitting body is made to take place by means of the flow of electric current through a conductor which may, or may not be, the actual electron emitter. At (B) is shown the method used for producing electron emission in the ordinary forms of battery-operated vacuum tubes. The heating current, supplied by a primary or storage battery, flows through a filament wire which gives off the electrons when it is heated to a red heat. At (C) the a-c heating current from a step-down transformer, flows through the electron-emitting filament. In some applications of thermionic emission it is preferable not to have the heating current flow through the body which is emitting the electrons. In these cases, it may flow through a separate heater device placed in mechanical contact with, or near, the electron-emitting substance, as shown at (D). This construction is employed especially when the heating current is obtained from an a-c source such as an a-c electric light circuit. In this case, it is common to use a step-down transformer T, to step down the 110 volts of the line to the low voltage required for the heater filament, as shown at (D). Here the heater is used merely to heat up the electron emitter by the conduction and radiation of heat from it. It performs no other function, although it may incidentally give off some electrons itself due to its high temperature.

This construction is used in the popular separate-heater types of vacuum tubes such as the 227, 224 and 235, designed to be heated with alternating current from the electric light circuit, as well as in the 236, 237 and 238 types designed especially for use in automobile radio receivers or d-c electric receivers, as shown at (D). The current flows through the heating filament bent in hairpin shape, which imparts its heat energy by conduction and radiation to the separate metal cathode or electron emitter which surrounds it, but which is electrically insulated from it by the insulating bushing.

The filament wire runs through two tiny holes drilled in the insulating bushing. The latter is made of some ceramic material such as "isolantite" which is a good heat conductor and also a good insulator even when it is heated to a red heat during normal operation by the filament. It conducts this heat to the closely fitting metal sleeve on its outside. The sleeve is coated with barium oxide or some other material which emits electrons freely at moderately high temperatures, and so acts as the cathode. In some tubes of this type designed so the cathode will be heated to its emission temperature quickly when the heater current is turned on, the insulating bushing is made thin to reduce its mass so it will heat up more quickly. In some quick-heater tubes, the insulating bushing has been omitted altogether, the designers relying entirely on the small space between the heater filament and the metal cathode sleeve, to keep the heater filament from touching, and making electrical contact with the metal cathode sleeve. These tubes heat up very quickly, but short-circuits frequently occur when the filament or other parts are bent out of line by accidental severe jars or shocks during shipment.

Some substances do not emit electrons in any appreciable quantities, even though they be heated to extremely high temperatures. The electron-emitting characteristics of various substances will be studied later.

265. Producing electron emission by light: It has been found that a similar electronic emission occurs when light rays of certain frequencies, colors, or wavelengths, are made to fall upon certain materials, as shown at (E) of Fig. 189. This is known as the *photo-emissive* effect; the emission of electrons by this method is known as *photo-electric emission,* and devices employing this effect are known as *photo-electric devices.* The

photo-electric cell, or *tube,* employed in television and sound picture equipment, and in many commercial counting, sorting, and controlling devices operates on this principle. The principles of photo-electricity have been known to the scientific world for over 40 years, but it was not until the recent development of television and sound pictures that practical photo-electric cells were made available commercially.

The energy of the electromagnetic light rays striking the substance is imparted to its electrons, enabling them to acquire sufficient energy and velocity to overcome the force of attraction at the surface of the substance, and escape with a velocity which depends on the energy in the light rays and the amount of energy they must expend to overcome the surface force. Those which happen to be near to the surface have to overcome only the surface force, while those further in the interior will have to do an extra amount of work in forcing their way out.

The photo-electric effect is very interesting because its discovery has resulted in further strengthening the electron theory and the quantum theory explained in previous chapters. It has been found by experiment that the maximum velocity of emission by this effect is independent of the temperature of the cathode and is also independent of the *intensity* of the light with which the cathode is illuminated. If the intensity of the light is increased, only the *number of electrons emitted* increases, but their velocity stays the same. The frequency, color, or wavelength of the light (see Fig. 163) is the only factor that influences the velocity of the emitted electrons, when considering any one substance. The higher the light frequency (the nearer the light is toward the ultra-violet end of the spectrum) the higher is the velocity of the emitted electrons. For a given light frequency (color), the emission depends on the electron affinity of the substance upon which the light is acting. Therefore all substances do not give off electrons with equal ease when exposed to light.

Zinc gives off electrons quite freely only when exposed to light rays of very high frequency, such as ultra-violet light. Other metals such as potassium are very sensitive to light in the visible part of the spectrum. Potassium is therefore used in some photo-electric cells where its function is to emit electrons in proportion to the amount of ordinary white light that is permitted to fall upon it. Other of the alkali metals which emit electrons when subjected to light rays are sodium, lithium, caesium and rubidium. These will be studied later when a detailed study of photo-electric cells is made in Chap. 32.

The source of light may originate in some common light source such as an incandescent lamp, daylight, etc., or may originate in fluorescent chemicals which have been caused to emit the required light by reason of previous exposure to electromagnetic radiations from some other source.

266. Electron emission by electron bombardment: Electrons may also be forced out of a body by the impact of other electrons projected against its surface. This action is called *secondary emission.* Thus, X-rays are electromagnetic radiations produced by causing a stream of electrons to impinge on a target. In order to produce penetrating X-rays, the velocity and frequency of the stream of electrons must be quite high, which means that the applied voltage causing the movement of the stream of electrons must be quite high. At the lower voltages employed in ordinary vacuum tubes, the action of the electron stream impinging on a metal plate may cause a considerable *secondary emission* from the plate, especially where the plate voltage is high. This will be referred to again in Art. 318. When the velocity with which the electrons strike the metal plate

increases beyond a certain critical value, one primary electron can knock out more than one secondary electron from the plate. This is the principle on which the *dynatron* operates, (see Art. 636).

267. Electrons from gases, ionization: If a stream of electrons is caused to move through a gas, they will bump into the larger and heavier atoms of the gas. (The hydrogen atom, which is the simplest and lightest of all atoms (see Fig. 17) has a mass approximately 1,800 times as great as the mass of the electron. The masses of the more complex atoms of other chemical elements is proportionately greater.) If the electrons are moving with a high enough velocity, they will split up the atoms of the gas when they collide with them and electrons will be detached from the atoms, leaving the remainder of each atom with an unbalanced positive charge due to the loss of the negative charge of the electron knocked off, as shown at (F). This causes these atoms to be ionized positively, and the freed electrons join the stream of moving electrons under the directive force of the applied e.m.f., possibly colliding with some atoms on their way and thus helping to liberate more of them. The positive ionized atoms are attracted toward the source of electrons by the negative charge and move slowly toward it. The gas is then said to be *ionized.* Electrons are detached from the gas atoms by collision with them, so this process is usually referred to as *ionization by collision.*

The least energy with which an electron can collide with an atom and completely detach an electron from the atom of any gas or vapor is usually expressed in terms of the voltage required to impart enough velocity to the moving electron to enable it to strike the atom with sufficient force to dislodge an electron from it. This is known as the *ionization voltage.* The ionization voltage required to ionize mercury vapor is 10.4 volts, for helium it is 29 volts, for hydrogen it is 13.6 volts, etc.

If the electron strikes with insufficient velocity and force to completely dislodge an electron from the atom, against the attractive force of the nucleus, the energy of the striking electron is gained by the gas atom. The energy gained by the gas atom manifests itself at first by a displacement of one of the electrons of its inner orbit, to an outer orbit. This condition of instability of the atom does not last long, and the displaced electron will soon return to the inner orbit. Since an electron in an outer orbit possesses more potential energy than one nearer the nucleus, it must get rid of this energy as it moves from the outer orbit back to an inner one. This takes place in the form of a small quantity of radiated electromagnetic energy (a quantum) but it is of such a nature that it will not produce the sensation of sight.

If the electron strikes the atom with sufficient velocity to dislodge an electron to a point outside of the atom beyond where any possible orbits of its electrons exist, then in this position the potential energy of the electron is a maximum and it will be attracted along with the moving stream of electrons toward the source of positive charge which is causing the motion. Meanwhile, the positive ion will migrate in the opposite direction, toward the source of electrons, and when it gets near to it, it will attract an electron to it with sufficient velocity to bring it into one of its orbits. In doing so, it radiates the excess energy in the form of light of a characteristic color depending on the chemical nature of the gas. Thus, in the neon gas used in the familiar electric display signs which possess the characteristic red or pink light, the light is due to the ionization of the neon gas in the tube, caused by the application of a voltage to it to cause the electron stream to flow through the gas at a high velocity. The blue glow observed in vacuum tubes that are not well evacuated is also due mostly to the impact of the electron stream on the gas atoms which may be present. This fact is used as a test for the presence of gas, during the evacuation of vacuum tubes.

The tungar rectifier tube employed in battery chargers operates by ionization of the argon gas it contains. The electron stream is furnished

by a filament which is heated to incandescence by an electric current. A positive potential applied to a carbon plate in the tube attracts these electrons at high velocity. On their way they collide with atoms of the gas and liberate many more electrons by collision. These liberated electrons are immediately attracted by the plate, and move to it. This makes the electron stream and the current flowing through the rectifier and available externally for useful purposes, much greater than if no ionization took place.

268. Choice of electron emitter: From the foregoing, it is evident that a stream of electrons could be obtained for use in vacuum tubes in either of the three ways described. Up to the present time, the method of heating a suitable substance which gives off electrons when it is heated to a red heat by the passage of an electric current through a heating filament, has been used exclusively in vacuum tubes. Much research work is being carried on toward the development of vacuum tubes in which electrons are emitted by some method less crude and less wasteful of energy than by the application of heat.

Some experimental tubes have been produced in which an ionized glow discharge was employed to produce a field between a cathode and a plate. Lately, the principle of photo-electric emission has been applied to produce some very interesting experimental photo-electric vacuum tubes. In one of these, a single source of ultra-violet light placed at the center, illuminates as many as five independent cathodes placed around it, each one being coated with a light-sensitive material which gives off electrons freely due to the action of the light shining upon it. One of the problems encountered in this work, is that of increasing the very limited amount of electrons emitted by photo-electric devices of the present ordinary design with the photo-sensitive materials now available. The current flowing in photo-electric cells is in the order of *microamperes* rather than the current of *milliamperes* which exists in ordinary thermionic vacuum tubes. Such small currents are troublesome to handle, for slight variations affect them greatly. Another problem in these devices, is the development of an economical source of absolutely steady light for causing the electron emission. Any variation in the *intensity* of the light at once causes a change in the electron emission, resulting in a change in the current through the device. Also the methods of producing light at the present time are much less efficient from the standpoint of the loss of energy, than those of producing heat. Nevertheless, new developments along these lines may be expected in the next few years, for the elimination of the heaters and the heater current in modern vacuum tubes would result in the elimination of many of the troubles and ills to which radio equipment is now subjected.

Since our present forms of vacuum tubes employ electrons produced by heating certain substances, we will now study their operation.

269. Two-electrode vacuum tube: In 1896 Dr. J. A. Fleming investigated the "Edison effect" described in Article 262. His work resulted in the development of the two-electrode tubes shown in Fig. 190. It was referred to at that time as the *Fleming Valve*, and the term *valve* is still used in Europe. to designate what in America is familiarly known as a *vacuum tube* or *electronic tube*. The term *valve* is roughly descriptive of the real operation of the tube.

As shown at (A) of Fig. 190, a V-shaped filament is connected across the terminals of a battery (called the "A" battery), or other source of e.m.f., with an adjustable resistor R, in series, to control the current flowing through it, and therefore its temperature. The tungsten filament wire, is mixed or coated with a substance such as barium oxide which emits electrons freely when heated to a low red heat. In order to prevent rapid oxidation and burning up of the filament when it is heated to incan-

descence by the current flowing through it, it is sealed in a glass bulb from which every trace of air has been pumped out. This is represented by the circle around the tube elements in the diagram. The ends of the filament are sealed into the glass bulb, to prevent any leakage of air. Removing the air from the bulb also performs the function of removing these comparitively large air or other gas atoms from the space surrounding the filament, for they, having a mass over 1,800 times as great as that of an electron, would block and interfere with the emission and movement of the electrons, as explained later. When the filament is heated, it will emit electrons in rapid motion. These will form a sort of miniature cloud around it, as shown at (B) of Fig. 189, much like the cloud of water vapor which hovers over a pan of boiling water. These electrons have no particular place to go, and since they are all negative charges of electricity, return to the filament. The collection of all of these negative charges of the electrons in the space around the filament forms a rather strong negative charge

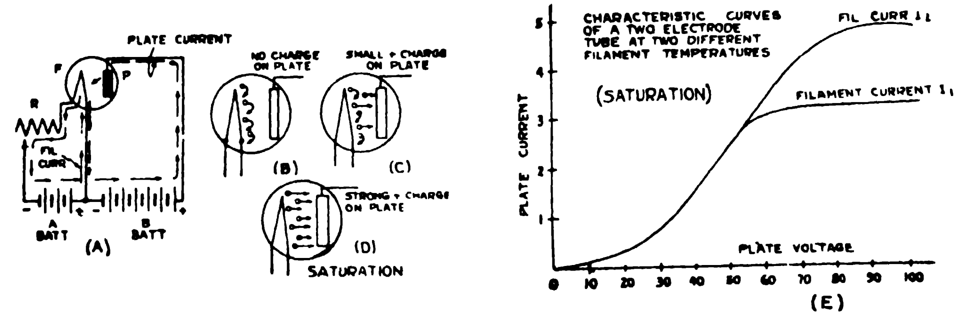


Fig. 190—Arrangement of the elements and action of the 2-electrode vacuum tube. The plate saturation characteristics produced by complete attraction of all of the emitted electrons is shown at the right.

called the *space charge*, which will tend to repel back to the filament, those negative electrons which are being emitted after them (like charges repel each other).

If now, a metal plate P, or second electrode is sealed into the glass bulb as shown at (A), we have a duplication of the effect which puzzled Edison. If the plate is kept at a positive charge or potential with respect to the filament, either by connecting it to the positive terminal of a second battery (called the "B" battery), or to some other source of unidirectional e.m.f., as shown, to make the charge stronger, it will attract the negative electrons to it (a positive charge attracts a negative charge) as soon as they are emitted from the filament. If the plate is made negative, that is a negative charge is put on it, by connecting it to the negative leg of the filament circuit or to the negative terminal of the B battery, with its connections reversed, it will repel the electrons back to the filament, and none will go to the plate. We are not interested in the latter connection, for tubes are not operated this way in practice. It is evident that the negative end of the B battery may be connected either to the negative end of the A battery or to the positive end of the A battery. Very little difference results from either connection. In some battery operated receivers the A + and B — terminals are connected together, in others the A — and B— go together. The latter method has several advantages, one of which is convenience in grounding the A— and B— lines both to the metal chassis of the receiver.

With the plate positively charged, a steady stream of electrons will be attracted from the filament to the plate and will then continue their journey around the circuit from the plate to the B battery, through the B battery from the + to the — terminal, up through the filament leg on the right, and back to the filament. We thus have a *circulation of free electrons from filament to plate* and back through the B battery to the filament or electron emitter again, just as many returning every second as are emitted during that second, i.e., there are no electrons lost or gained. This circulation of electrons in the *plate circuit* constitutes the flow of electric current, called the *plate current* or *emission current*, in the opposite direction, i.e., from *plate to filament*, for the reasons mentioned in Article 25. It is important to keep in mind always this difference in direction between the plate current flow and the electron flow in the vac-

uum tube and all other electric circuits. At (A) in Fig. 190, the directions of both the filament *current* and the plate *current* flows are indicated by the arrows (from the + terminal of the source of e.m.f. to the — terminal), at the left of Fig. 191 the relative directions of both the electron flow and plate current flow in the plate circuit are indicated. If a milliammeter were connected between the B battery and the plate, it would indicate a flow of current in the plate circuit, just as the galvanometer used by Edison in his test indicated.

It is evident that the apparent mystery in the effect which Edison noted in his incandescent lamp was really due to the fact that while it was then supposed that the space between the filament and the plate was absolutely empty, actually it was filled with moving electrons emitted by the hot filament, and constituting the flow of electric current which was indicated on his meter. No electrons are usually given off by the plate, because it is maintained at a low temperature.

270. Saturation current: Let us study this interesting device further, with particular regard to the manner in which the plate current varies and the means by which such variations may be brought about. Obviously, the number of electrons which pass in a given time across the space from the filament to the plate and then around through the external plate circuit back to the filament, is limited by the number of electrons emitted by the filament and by the ability of the plate to attract the electrons so emitted. The electron emission for a given filament, depends on its temperature, which in turn depends upon the heating current flowing through it. The ability of the plate to attract the negative electrons depends upon the difference of electrical potential maintained between the plate and the electron emitter by the B battery.

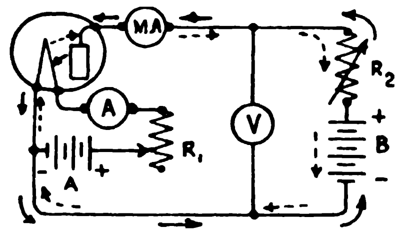
Due to the fact that there is a uniform I $\times$ R drop through the filament due to its resistance and the current flowing through it, different points along the filament are at different potentials, so that we must decide upon some one definite point on the filament as the reference point from which all differences of potential in the tube shall be measured. It has become standard to consider this point to be the *negative end* of the electron emitter or cathode. In tubes of this kind, since the cathode is the filament, the negative terminal of the filament is considered as the reference point from which all differences of potential are measured. Thus, in speaking of the plate potential or voltage, we mean the difference in potential between the plate and the negative terminal of the filament, etc. (In the case of separate-heater type tubes, the *cathode* is the potential reference point in the tube.)

It follows then, that the plate current is limited by the filament current and the plate potential. *Therefore, the plate current of a two electrode tube may be varied either by varying the plate potential or the filament current.*

Let us next investigate just how the plate current changes with variations of either of these two factors:

Experiment: Connect up the two-electrode tube as shown at the left of Fig. 191. (An ordinary 3-electrode type 201-A tube can be used with its grid terminal connected to its plate terminal so they both perform the function of a plate. This will then be

equivalent to a 2-electrode tube.) The actual set-up of the simple apparatus for this test is shown in the photograph at the right of Fig. 191. A variable resistance R_1 having a maximum resistance value of about 30 ohms is connected in series with the 0-0.5 amp. d-c ammeter in the filament circuit, as shown. This rheostat is the one shown in the foreground in the photograph. A variable high resistance (about 0-50,000 ohms) shown in the rear, is connected in series with a B battery or other source of steady d-c potential of about 90 volts, and a voltmeter having a range at least from 0-100 volts are connected as shown. Set the filament current constant at about .2 amperes, and starting with zero plate voltage, take readings on the plate milliammeter and voltmeter for each increase of 10 volts in the plate potential. Set the plate potentials carefully by means of the resistor R_2. Now set the filament current fixed at 0.25 amperes and repeat the test. It may be necessary to increase the plate voltage above 90 volts in order to reach the condition where the plate current increases very little with each 10-volt increase of plate voltage. Each test should be continued until



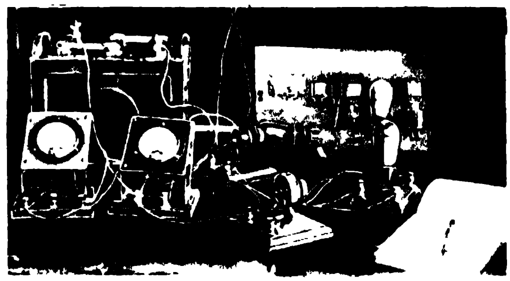


Fig. 191—Left Apparatus connections for measuring the characteristics of a 2-electrode vacuum tube
Right. Actual set-up of the apparatus for this test.

this condition is reached. If it is necessary to go above the voltage limit recommended by the manufacturer for the tube used, keep this voltage applied only long enough to make the test. Now plot a graph with plate voltage as abscissae (horizontal scale) and plate current in milliamperes as ordinates (vertical scale). Do this for each set of readings, one for the filament current at .2 amps. and the other for the filament current at .25 amps.

The graphs will be of the general shape shown at (E) of Fig. 190. They show at a glance how the plate current varies as the plate potential or voltage is increased. An examination of the curve for the lower value of filament current shows that as the plate voltage is increased, there is a rapid increase in the plate current at first. After a certain value of plate voltage is applied, there is no appreciable increase produced in the plate current by increasing the plate voltage. This is shown by the fact that the curve becomes horizontal when this point is reached. If the curve for the higher filament current is plotted, it is found that the curve coincides at the lower end with the one already plotted, but that the plate current continues to increase above the bend reached before. After a certain value of plate potential is applied, the plate current again fails to increase for further increase in plate potential. In this case, however, a higher limit of plate current has been obtained from the tube than before. If a series of similar curves were constructed, with each one corresponding to a definite filament current, the same characteristics would be noted in each, namely a part where the plate current increases with plate voltage, and a part where the plate current no longer increases if the plate voltage is increased.

From this family of curves, it is at once evident that with any constant filament current there seems to be a definite plate current which cannot be exceeded. Moreover, this set of curves shows us that if the filament current is increased to a higher fixed value, the maximum value of the plate current also increases. From this data, it is evident that some condition exists within the vacuum tube which limits the amount of plate current which can flow in it. In the second place, it seems quite certain that this limiting factor depends upon the filament temperature, which in turn is controlled by the filament current. We can now summarize these experimental facts by

saying that the maximum plate current which can flow for a given plate voltage depends upon the temperature of the filament. We will now see the reason for this.

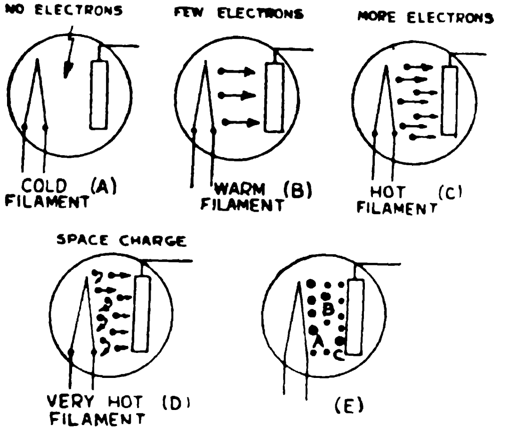
The proportion of the emitted electrons which are attracted to the plate, depends on the strength of the plate potential. When the filament temperature is kept at a constant value, and the plate potential is gradually increased, the number of electrons attracted to the plate per second, and therefore the current in the plate circuit, will gradually increase as shown at (B) and (C) of Fig. 190. This will continue until a condition is reached where the plate attracts the electrons over to it at the same rate as they are emitted from the filament, as shown at (D). It is evident that when this condition is reached, any further increase in the plate potential will not cause any increase of the plate current, since if the plate is attracting *all of the electrons* as fast as they are given off by the filament, it cannot attract a greater quantity unless the filament is made to give off more electrons per second by increasing its temperature. This maximum plate current, beyond which there is no increase for increased plate potential, is known as the *saturation current* of the tube, for the corresponding filament temperature and plate voltage.

For any given filament temperature then, there is a definite value of maximum plate current which can be obtained, *occurring when the plate attracts the electrons at the same rate that they are emitted.* It is essential that a tube be designed so its filament is able to emit electrons at a sufficiently rapid rate so that *saturation* never occurs at the normal filament current and plate voltage at which the tube is to operate in practice. Modern tubes are designed with electron emitters able to supply an ample quantity of electrons.

271. Space charge and the screen grid tube: Let us now keep our tube connected as in Fig. 191, and with the plate potential fixed at about 60 volts, vary the filament current from 0 to about 0.3 ampere (taking the readings above 0.25 ampere quickly), taking readings of the plate current and filament current for every increase of about .02 ampere of filament current. This is repeated for a fixed plate potential of about 90 volts, and graphs are plotted from the readings as shown at (F) in Fig. 192. It will be noticed that the plate current increases as the filament current and temperature of the filament are increased, up to a certain value, after which further increase of filament current has no effect on the plate current. If the plate potential is then increased, a larger value of plate current may be obtained, but a critical point is again reached where further increase of filament current does not result in any increase in plate current. Let us see why this is:

When the filament is cold, since no electrons are being emitted, no electrons and current flow in the plate circuit, as shown at (A) of Fig. 192. If the filament is gradually heated, by increasing the current from the "A" battery, it begins to give off electrons when it has attained a dull red heat, as shown at (B). The number of electrons emitted by the filament increases approximately as the square of the excess filament temperature above red heat. At any instant, the space between the hot filament and plate contains those emitted electrons moving on toward the plate, to be absorbed there. As the filament current is increased and the filament temperature is thereby raised, as shown

at (C) and (D), the rate of emission of the electrons increases. Therefore, at any instant the number of electrons present in the space between the filament and the plate depends on the rate of emission by the filament and the rate of attraction by the plate. The steady increase of filament temperature increases the electron emission from the filament and also the number in this space. As these electrons are all negative charges of electricity, the cloud of them around the filament causes a combined negative charge in the space around the filament. This tends to repel back any electrons emitted from the filament. Also, between the filament and the plate there is an electric field due to the positive plate. This tends to pull the emitted electrons toward it; while at the same time there is this other electric field due to the cloud of electrons around the filament, tending to repel them back to the filament. This latter charge is known as



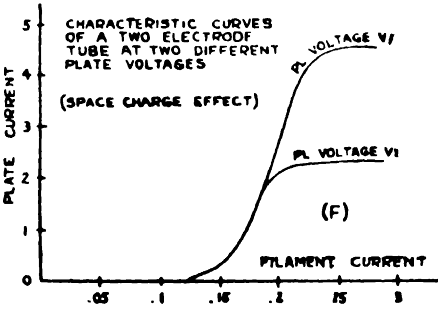


Fig 192—Space-charge effect of the cloud of negatvie electrons around a filament This combined negative charge repels the electrons back to the filament

the *space charge*; it is the negative charge due to the accumulated electrons in the space between the filament and plate. A more detailed explanation of this follows:

At (E) of Fig. 192, let A, B and C be three electrons occupying different positions at some instant while on their way to the plate. Electron C is near the plate and is therefore attracted strongly by the positive charge on the plate, and is repelled toward the plate by the negative charges of all the electrons back of it, since they have like charges. Therefore, it will undoubtedly go to the plate. Electron B is attracted by the plate, and repelled back by the elctrons between it and the plate. Electron A is urged toward the plate by the hot filament, is attracted toward the plate by the positive charge on the plate, and is repelled back toward the filament by the combined negative space charge due to the individual negative charges of all the electrons in the space between it and the plate. Whether it will move toward the plate or re-enter the filament depends upon which of these opposing forces is greatest. If the plate voltage is made high enough, the plate will of course attract it over to itself.

It is evident that when the electrons moving across the space between the filament and plate become so dense that their combined negative charge—"space charge"—is equal to, or greater than, that of the plate, they neutralize the action of the plate and the electron flow to the plate cannot increase even though the temperature of the filament is raised. When this condition results, any additional electrons emitted into the space of the tube by the filament, will make the space charge overbalance the plate charge and repel the excess emitted electrons back to the filament as shown at (D). In order to increase the plate current under this condition, the attractive force of the plate must be increased by increasing the plate voltage applied to it. Thus, for every fixed value of plate voltage, there is a certain value of filament temperature beyond which no increase in plate current can be obtained.

As a result of this repelling action of the electric field caused by the space-charge of the electrons moving in the space between the filament and the plate, it is evident that the resultant effective electric field intensity and attractive force of the plate for the emitted electrons, is much less than we would expect to find from a consideration of the applied value

of the B battery voltage alone. Since the attractive effect of the positive charge on the plate is lessened by this space charge, it follows that fewer electrons will move from the filament to the plate during each second for a given filament current and plate voltage, and consequently a smaller plate current will flow. As we shall see later, the harmful effects of the space charge are eliminated by the construction employed in the *screen-grid* tube. In this, an open-wire mesh or spiral wire is placed around the heater or filament and is kept at a positive potential with respect to it and thereby neutralizes the space charge. It is of open construction to allow the electrons to shoot through its open spaces freely and it is kept at a positive potential much lower than that of the plate so the latter will tend to draw the electrons right through the open spaces in it.

An idea of how large a number of electrons are travelling from the filament to the plate and back through the external plate circuit in the modern vacuum tube, may be gained from the fact that an ordinary 227 type tube has a plate current of 5 milliamperes flowing when the plate voltage is 180 volts. Remembering that a flow of one ampere of current constitutes the flow of 6.28×10^{18} electrons flowing past every point in the circuit each second, we can easily calculate that in this tube 3.14×10^{16} electrons are flowing from the filament to the plate every second. This means 3.14 times a thousand million million electrons per second. The cathode supplies these electrons.

272. Two-electrode rectifier: The two-electrode tube just described was used in the early days of radio as a detector in place of the crystal detector described in Chapter 16. It is still used as a detector (commonly called a *diode detector*) in some radio receivers. It finds its greatest use however, as a rectifier of alternating current in high-voltage B-power supply units, for which it is marketed in the special form known as the '81 type rectifier tube. When an alternating radio-frequency signal voltage, or a-c line voltage is applied to the plate circuit instead of the "B" battery, no current flows during each half cycle when the plate is made negative with respect to the filament, since the electrons do not reach the plate on account of the repulsion from it; but electrons and current do flow when the plate is made positive. Thus only one-half of each alternating current voltage wave is effective in causing a plate current to flow and the tube acts as a half-wave rectifier. The half-wave current flowing in its plate circuit is of the form shown at Fig. 151. When another plate is added as in the '80 type tube, we have a full-wave rectifier. Vacuum tube rectifiers play an important part in the successful operation of electric receivers, for changing the alternating current obtained from the a-c electric light socket, to direct current. They will be studied in detail later, in Chapter 27.

273. Three-electrode tube: The development of the two-electrode tube by Dr. Fleming was the forerunner of the modern three-electrode vacuum tube which was invented by Dr. Lee De Forest in 1906. He called it the *audion*. probably because he found that on inserting a third

electrode (the grid) between the filament and plate, he obtained a large increase in sensitivity, and louder volume of sound when this arrangement was used as a detector in place of the crystal detectors and coherers then in use. This resulted from the grid's action in responding to the feeble flow of energy collected by the antenna, and so affecting the plate current (electron flow from filament to plate). The introduction of the grid also made possible audio-frequency amplification, radio-frequency amplification and the adaptation of the vacuum tube to radio-telephone and telegraph transmission where it is employed as a generator and modulator of high-frequency currents. There is no doubt that without the

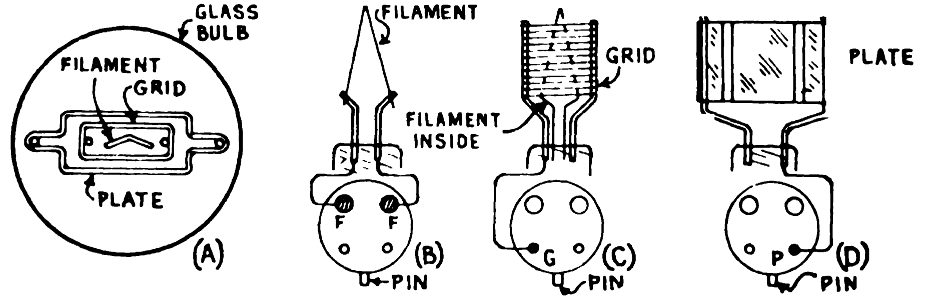


Fig 193—Relative positions of elements in a 3-electrode tube The connections between the elements and the base prongs are illustrated looking up at the bottom of the tube.

"triode" or three-element vacuum tube, radio telephony could never have even approached the state of perfection it enjoys today.

The three-electrode tube is essentially the same as the two electrode type, but has in addition a third electrode or *grid* in the form of a metallic mesh, (or usually a coil of very fine wire with widely spaced turns), placed between the filament and the plate. The elements are arranged as shown at (A) of Fig. 193 which shows a top view looking down on the top of the tube. The filament is surrounded by the grid (shown in elevation at (C), and the grid is surrounded by the thin metal plate (shown in elevation at D). In this way, the electrons emitted from all sides of the filament wire are attracted by the plate and must flow through the open spaces in the grid winding or mesh.

The connections made from the grid, filament and plate to the prongs of the tube base, as they would appear when looking up at the bottom, are shown at (B), (C) and (D). On one side of the base of some tubes is a small pin which acts as a guide when inserting the tube in the old shell-type socket. In the three-electrode tube, the two ends of the filament connect to the two prongs of larger diameter as shown. One of the grid supports connects to one of the remaining thin prongs. The other grid support serves no purpose other than to support one side of the grid wires. One of the plate supports is connected to the remaining thin prong on the base.

In making radio diagrams it is not convenient to draw the parts of the tube as shown here. Therefore the symbol shown in Fig. 194 is generally used to indicate the glass bulb containing the filament, grid, and plate. The symbol places the grid between the filament and plate just as it is actually placed in the tube itself. The symbols commonly used to represent the various common types of vacuum tubes will be found in the Symbol Chart in Appendix A at the back of this book.

Since, in the two-electrode tube, with a given filament temperature the rate of flow of electrons depends on the potential of the plate, if a third electrode, or "grid," is inserted between the filament and plate so that the electrons must go through the open spaces in it on their way to the plate, then, by varying the potential of this third electrode, the electron flow can be controlled. Since the grid is in the midst of the space charge, when it is made more positive (with respect to the negative terminal of the filament) by means of a battery (called the "C" battery) as shown at (B) of Fig. 194, or some other source of potential (such as the radio signal voltage), it tends to neutralize the effect of the space charge, thus reducing the opposing force of the space charge and consequently making

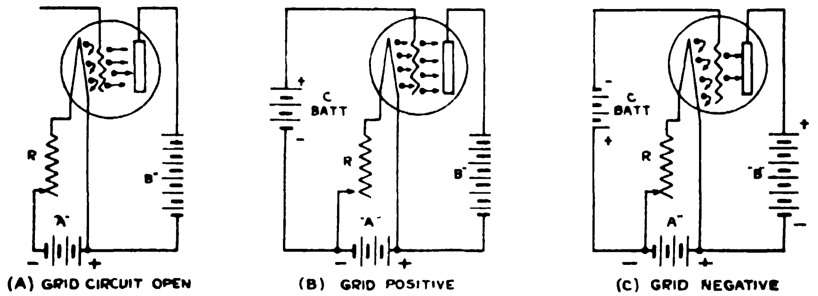


Fig. 194—Action of the 3-electrode vacuum tube with (A) grid circuit open; (B) grid positive; (C) grid negative.

it easier for the emitted electrons to get to the plate. This therefore increases the electron flow and the plate current.

When it is made more negative (by connecting the negative terminal of a battery to it as shown at (C), or by some other source of e.m.f. such as the radio signal voltage), it assists the space charge in repelling more of the emitted electrons back to the electron emitter. Therefore the emitted electrons meet more opposition than ever in attempting to pass from the filament through the grid to the plate. Fewer of the electrons get through to the plate and consequently the plate current decreases. If it is made sufficiently negative, the plate current will be reduced to zero that is, the flow of electrons through the grid to the plate will be shut off completely. The grid therefore acts like a valve in controlling the flow of electrons (plate current) in the tube. It is for this reason that it is commonly referred to as a *valve* in Europe. When the grid is made positive, it collects a few electrons itself, acting like a second plate, giving rise to a current in the grid circuit from grid to filament. This should be remembered, as it becomes important in the practical use of the three-electrode tube as an amplifier in modern receiving sets. The flow of grid current is generally undesirable in tubes used as amplifiers (see Art. 340).

This effect of the grid in either increasing or decreasing the electron flow and the plate current, is of exceedingly great importance in radio work.

It is this effect that enables us to control comparitively large currents in the plate circuit either by impressing the varying *signal-voltage* upon the grid ("input") circuit, so that it drives the grid alternately "positive" and then "negative"; or else so that it serves to raise and lower the voltage of the grid above and below a sufficiently large steady negative voltage which is also applied to the tube. This latter voltage is called the *C-bias* voltage. In the latter case, the grid always remains "negative". The incoming alternating signal voltage merely makes it successively more and less negative from its C-bias value. This is the more common way of operating vacuum tubes as detectors and amplifiers.

274. Amplifying property: It is evident from the foregoing considerations, that the plate current in a three-electrode tube can be varied by varying any of three factors, the filament current, the grid potential, or the plate potential. *The grid of the tube, being much closer to the filament than the plate, can, when a potential is applied to it, control the electron emission far more effectively than the same potential applied to the plate.*

Suppose the grid potential of a tube is increased in the positive direction by, say, two volts. This would result in a plate current increase of, say, four milliamperes. Now, obviously, the plate current could also have been increased the same amount of four milliamperes by increasing the plate voltage instead of the grid potential. But it takes a considerably larger increase in plate voltage to affect the plate current to the same extent as that caused by a given increase in grid potential, since the grid is much nearer to the filament than the plate is, and therefore controls the electron flow more effectively. In the standard 201A tube a given grid voltage change will produce *eight times* as much plate current change as an equal change in plate voltage will. For a 224 type tube this ratio is about 400! That is, it requires *400* times as large a plate voltage change to affect the plate current to the same extent as that accomplished by the "control" grid. Consequently, the *voltage amplification factor* of the 224 tube is 400. We thus have a sort of trigger action here, a small voltage change applied to the grid varying the plate current just as effectively as a much larger voltage change on the plate would do it. The relative effects vary inversely as the cubes of the relative distances between the elements in the tube.

In a radio receiving set, we are interested in taking the very weak varying a-c incoming signal voltage set up in the aerial circuit and amplifying it greatly by making it produce large plate current changes in amplifying tubes arranged in proper circuits. Knowing that changes in plate current can be produced by either a change in grid voltage, a change in filament voltage, or a change in plate voltage, it is evident that the varying signal voltage could be applied in either one of these three circuits in the tube, as shown in Fig. 195, and it would produce a variation of plate current in each case. (We will neglect the fact that the signal must first be rectified in order to be heard in the phones.) If we connect a sensitive earphone or loudspeaker in the plate circuit as shown, any change in the plate current which flows through the magnetizing windings, will produce motion of the diaphragm. This will in turn produce sound waves. We are interested in finding out in which of these arrangements a given variation in signal voltage will produce the *greatest* corresponding variation in plate current, because the greater the variation in the plate current the larger will be the amplitude of vibration of the earphone diaphragm

and the louder will be the sound produced. At (A) the signal voltage is applied to the grid circuit, at (B) it is applied to the filament circuit, at (C) it is applied to the plate circuit. The exact mathematical relation for the amplification produced will be studied later.

If the incoming varying signal voltage is applied to the *grid* circuit it will produce much larger changes in plate current (depending upon the amplification factor of the tube used) than if it were applied to either the plate circuit or the filament circuit. Hence, since the volume of sound produced by the loud speaker depends on the amplitude of the plate current variations in the last tube, the circuits of all modern receiving sets are arranged so the varying signal voltages are applied to the grid cir-

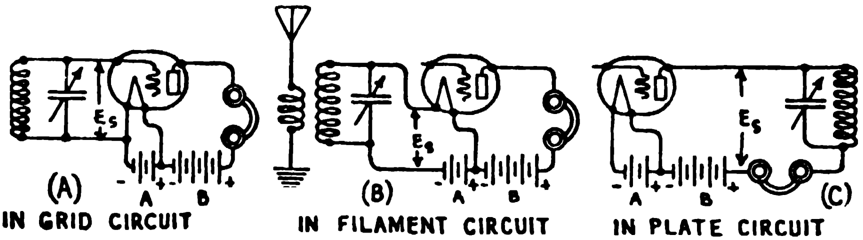


Fig 195—A signal voltage may be applied either in the grid, filament, or plate circuits of a vacuum tube as shown It has greatest effect on the plate current flow when it is applied in the grid circuit.

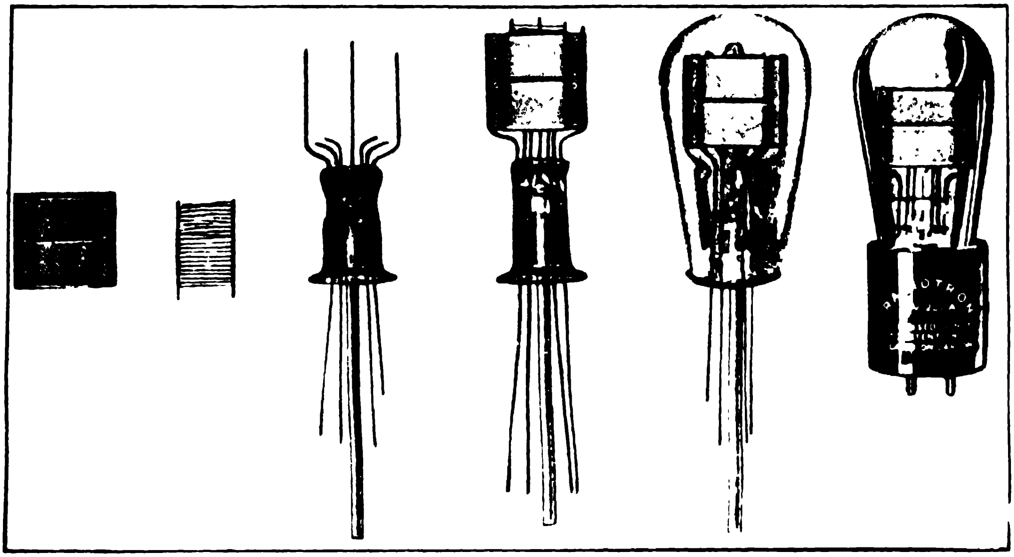
cuit (between the grid and electron emitter or cathode circuit), so as to cause corresponding variations in the grid potential and so cause similar larger variations in the plate current of the tube. The plate current variations are much greater in amplitude, but the same in wave form, as the applied signal voltage variations. This amplifying property of the three-electrode tube is one of its most valuable properties.

In Fig. 196 are shown the various parts of a typical 3-electrode tube designed for operation from batteries. Looking from left to right we have the plate, grid, mounted filament, three-electrode assembly sealed in a glass tube, and the complete tube. Notice that in the final tube the V shaped filament is in the center; around this is the spiral wire grid; and surrounding these is the metal plate. The filament in this tube is so fine that it is not visible in the illustration.

By employing an amplifier circuit with several tubes, an amplification of many thousand-fold may be obtained, since the plate current changes in the first tube act on the grid of the next tube, through the coupling device between them, and so on. The source of e.m.f. in the plate circuit (B battery or B voltage supply device) furnishes the energy which is added to that of the incoming signal by the vacuum tubes.

275. Characteristic curves: The behavior of vacuum tubes is best indicated by curves showing the relation between the various factors. The actual change in plate current due to a change in potential on the grid of

an ordinary radio detector or amplifier tube is shown at the right of Fig. 197 by the characteristic curve. This can be obtained, by measuring with a milliammeter, the plate current which flows when various measured voltages are applied to the grid. The curve is important, for it is by reason of the shape of its various portions that the tube is able to perform its many different functions. The use of a "C" battery (Fig. 194), presents a



Courtesy R. C. A. Radiotron Co

Fig 196—Several stages in the assembly of a '01-A type 3-electrode tube.

convenient way of placing any desired steady potential on the grid. It can be made stronger or weaker by varying the battery, and can be made positive or negative by reversing the connections of the battery. The connections of simple apparatus for making a test of this kind on 3-electrode tubes, are shown at the left of Fig. 197. In Fig. 199 a more elaborate tester for obtaining the characteristics of almost any tube, is shown.

The grid voltage can be varied and the plate current measured for each step, the plate voltage and filament current remaining constant. Three curves are given, one for each plate voltage. At zero grid potential(point A on the curve), the plate current has a definite value. As the grid potential is made more and more negative, the plate current decreases. As it is made more and more positive, the plate current increases. The curve has two distinct bends, one at B and one at C. These are called the "knees" of the curve.

It is interesting to note that in the region of the negative grid potential, since there is practically no grid current flowing, we have the condition where a mere change of the *potential* applied to the grid circuit, controls the plate current or *energy* in the plate circuit.

In the practical operation of a tube, the temperature of the filament and consequent electron emission must be sufficiently high so that the normal plate and positive grid voltages do not cause saturation of the tube (see Art. 270), for if this happens, the grid cannot control the plate current and the tube becomes inoperative.

276. Types of tubes: Although the 3-electrode vacuum tube just described is perhaps the simplest type in use in present day radio equipment, we shall find that the special construction features employed in the

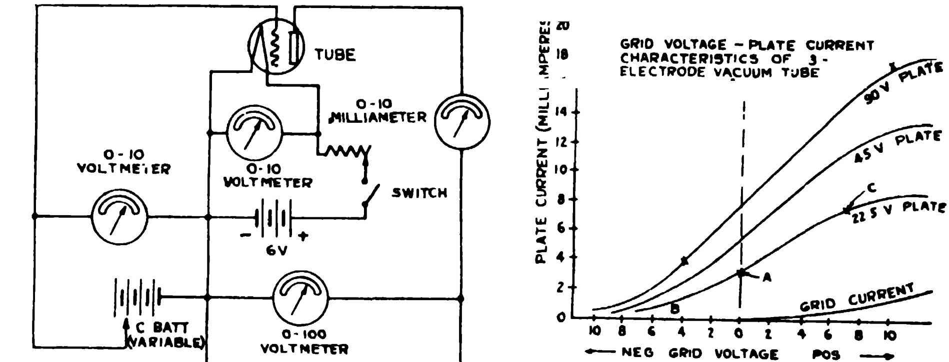


Fig. 197—Left: Circuit of testing equipment for finding characteristic curve data of a 3-electrode tube. Right: Grid-voltage plate-current characteristic of 3-electrode tube.

many other forms of tubes now employed as amplifiers and detectors, are all attempts to adapt the basic principle of the 3-electrode tube to more convenient forms of tubes having certain desirable special characteristics for the particular purposes for which they are employed, and which this simple tube does not have. For instance, the a-c heater-type tube was simply designed to overcome the necessity for using batteries to supply the filament current of the simple 3-electrode tube. The screen grid tube was designed to overcome the objectionable grid-to-plate capacitance existing in the simple tube. The pentode tube was designed to overcome the effects of secondary emission existing in it. Each type of tube was developed for a specific reason and purpose.

In order to understand how these characteristics differ, it will be necessary for us to study in detail just what the important operating characteristics of a vacuum tube are, and how the tube design influences them. This will form the basis of our study in the next chapter.

REVIEW QUESTIONS

1. Upon what fundamental principle does the operation of all forms of thermionic vacuum tubes depend?
2. Upon what fundamental principle does the operation of photoelectric tubes depend?

3. Explain the "Edison effect".
4. What is the difference between a vacuum tube and a valve?
5. What is an electron? How is the electron related to the atom?
6. Explain the phenomenon of electron emission by the application of heat. What is the cathode; the anode or plate?
7. How is the flow of electrons in a conductor affected by the difference of electric potential across it?
8. How does increase of temperature affect the emission of electrons from a heated body?
9. Is the popular idea that electricity flows from positive to negative really correct? Explain.
10. In a vacuum tube why do electrons flow from the filament to the plate but not in the reverse direction?
11. Why must the plate in a vacuum tube be kept relatively cold?
12. What happens if the grid is made (a) more positive with respect to the filament (b) negative with respect to it?
13. Describe a 2-electrode tube and explain its operation.
14. What is the most important use of two-electrode tubes at present?
15. Describe a 3-electrode tube and explain its operation. What is it used for?
16. Why is the plate current stronger when the filament is bright than when it is dim? Does it continue to increase indefinitely as the filament current and temperature are increased? Explain why.
17. What is the space charge in a tube and how does it affect the operation of the tube? Is it desirable?
18. How does the plate current of a tube vary as the plate voltage is increased? Show this by a graph. Can the plate current be increased indefinitely by increase of plate voltage?
19. What is the function of (a) the filament; (b) the plate; (c) the grid, in a vacuum tube? Draw a diagram showing their relative positions and shapes in a 3-electrode tube.
20. Why are the elements sealed into a glass bulb from which the air has been exhausted?
21. What is meant by ionization by collision?
22. What is "secondary emission"? Explain how it is caused.
23. Suppose you had a vacuum tube with its filament lit by an "A" battery, a pair of earphones, and a B battery connected in the plate circuit; and then connected a 4.5-volt dry cell C-battery with its positive terminal to A—, and the negative terminal to the grid. What would you hear; (a) under these conditions; (b) if you reversed the connections of the C-battery; (c) if you opened and closed the grid circuit rapidly; (d) if you connected in series with the grid circuit, a source of a-c voltage varying at

an audio frequency? Draw a diagram illustrating the connections in each case and give the reasons for your answers.

24. Explain in detail with sketches, 3 ways of heating a cathode in a vacuum tube in order to make it emit electrons.
25. Describe a simple construction arrangement for a vacuum tube operating on the photo-electric principle. State 2 of the handicaps which this type of tube must work under with present photo-electric sensitive materials and sources of illumination.
26. Draw the filament current—plate current characteristic curve of a vacuum tube (at two different values of constant plate potential) and explain the reasons for its shape at low, medium and high values of filament current.
27. Do the same for the plate voltage—plate current characteristic (at two different values or constant filament current).
28. What is the difference between thermionic emission, photo-electric emission, and secondary emission? How are each produced?
29. What is meant by emission current?
30. Draw the complete circuit connections for a 3-electrode tube with its filament and plate circuit batteries connected. By means of dotted arrows show the directions of the electron flow in the filament and the plate circuit. By means of solid arrows show the direction of the current flow. Explain!

CHAPTER 18

VACUUM TUBE CHARACTERISTICS

VACUUM TUBE CHARACTERISTICS — APPARATUS FOR DETERMINING STATIC CHARACTERISTICS — GRID POTENTIAL-PLATE CURRENT CURVES — PLATE VOLTAGE — PLATE CURRENT CURVES — V. T. NOTATION — V. T. CONSTANTS WHAT AMPLIFICATION FACTOR MEANS — SIMPLIFIED EQUIVALENT TUBE CIRCUIT — D-C PLATE RESISTANCE — PLATE IMPEDANCE — MUTUAL CONDUCTANCE — TUBE CONSTANTS FROM CURVES — MEASURING TUBE CONSTANTS QUICKLY — TUBE CHECKERS — DYNAMIC CHARACTERISTICS — RESISTANCE OUTPUT LOAD — IMPEDANCE OUTPUT LOAD — VACUUM TUBE BRIDGE — TABLE OF V. T. CHARACTERISTICS — REVIEW QUESTIONS.

277. Vacuum tube characteristics: The three-electrode vacuum tube is used to perform either of four major functions; that is, it may be used as a detector, amplifier, oscillator or modulator. The four and five-electrode tubes may be employed for similar purposes. In all of these cases, however, we are concerned with producing variations in the steady plate current of the tube by means of variations in the potential difference applied between the grid and cathode.

In the ordinary 201-A type tubes etc. ,the cathode is the filament itself; in the separate-heater type tubes, the cathode which emits the electrons is independent of the heater filament. In any case, the *cathode* is the part of the tube which emits the electrons; the *anode* or plate, is the part to which these emitted electrons are attracted.

In practice, the filament (or heater) voltage of a tube is adjusted to a certain fixed value specified by the tube manufacturer, depending on the particular design of the heater of the tube. Then the correct filament current will flow. Thus the filaments of 201A, 112A and 171A tubes are designed to take 0.25 amperes at 5 volts; those of the 227, 224 and 247 tubes take 1.75 amperes at 2.5 volts, etc. Under ordinary conditions, the voltages and currents specified for the heater filaments by the manufacturers, are such as to operate the filament at a temperature which will insure an operating life of at least 1,000 hours and a sufficient supply of emitted electrons from the cathode for proper operation of the tube. Consequently, we may forget these two constants of a vacuum tube because they are fixed in value and set by the designers and manufacturer. We must remember only to supply the proper voltage at all times.

If the filament voltage and current are fixed, the plate current still depends upon two or three variable quantities. In the case of the

three-electrode tube, the grid and plate voltages affect it; in the four and five electrode types (screen and pentode tubes) the screen voltage also affects it. The manner in which these variable factors affect the plate current controls the important characteristics of the tube, and may be shown best by means of graphs called *characteristic curves*, somewhat similar to those discussed in the previous chapter. Since there are several variable quantities in tube operation, the determination of the tube characteristics consists of keeping the voltage applied to the filament constant, varying the voltages applied to the other electrodes, and measuring the resulting currents which flow. We shall first consider the *static character-*

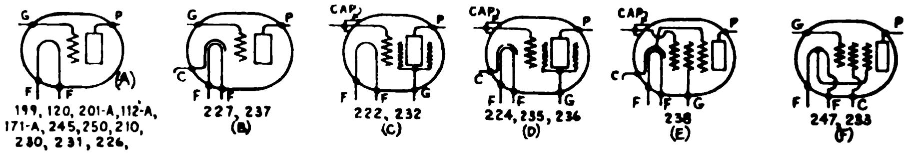


Fig 198—Arrangement of the electrodes in standard types of vacuum tubes in use in the United States.

istics, i.e., the characteristics measured at steady values of potentials and currents. As we shall see later, these characteristics do not exactly represent the conditions under which tubes operate in most practical circuits, but they are very helpful in our study of vacuum tubes nevertheless. The characteristics which are obtained with alternating potentials applied to the grid circuit are called the *dynamic characteristics* and really represent the actual working conditions of the tube. They require more elaborate apparatus for their determination however, and for all ordinary purposes of tube study, the static characteristics are considered as representing the operating condition of the tube fairly accurately.

The dynamic characteristics differ from the static simply because in actual tube operation the varying voltage applied to the grid circuit causes the plate current to vary. This varying plate current flowing through the usual earphones, loudspeaker winding, plate coupling resistor or transformer primary connected in the plate circuit produces a varying fall of potential in it. This being subtracted from the applied steady plate voltage at every instant, causes the actual effective difference of potential between the plate and cathode of the tube to vary. The effective plate potential therefore continuously varies with the variations of grid potential and plate current. This produces a further change of plate current at every instant, which of course is not shown by the static characteristic curves.

278. Apparatus for determining static characteristics: The data for the static characteristic curves of practically all types of tubes may be obtained by means of a tube tester employing the circuit arrangement shown in Fig. 199. This is a very useful piece of apparatus for any school or home laboratory.

Since there are at present five really different terminal arrangements on standard vacuum tubes employed in the United States as shown in Fig. 198 (D and E have the same socket-terminal arrangement) this tester makes use of five separate tube sockets with their terminals suitably connected in parallel so that the proper connections are automatically made to the heater, grid, plate and screen grid electrode (if it has

one) of the particular tube tested, provided that tube is placed in the proper socket as marked in the diagram. When testing tubes which do not have a screen grid, there will be no reading on the screen voltmeter and milliammeter of course. The values shown for the battery voltages and the ranges of the various instruments, will enable tests to be made on all of the types of tubes listed in the diagram. For greater accur-

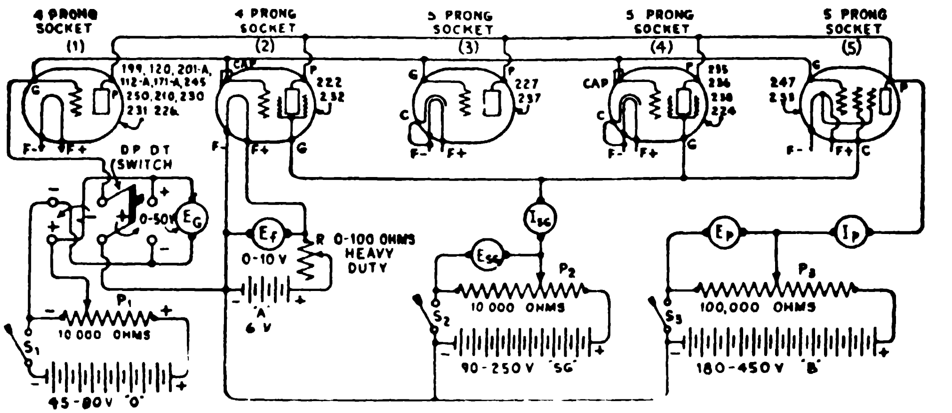


Fig 199—Tester arrangement for obtaining static characteristics of any type of tube shown in Fig 198

acy when testing those types of tubes in which the voltage and currents are rather low, it is advisable to use meters of lower ranges in order to secure larger scale deflections. Meters provided with adjustable shunts or multiplier resistors are of course very valuable in this work. It will be noticed that all voltages are arranged to be supplied by batteries. This is really preferable in most laboratory work, as the voltages will be steady. If desired however, the plate and screen voltages can be supplied by a well designed standard B-eliminator connected in place of the B batteries. The proper filament voltage for the particular tube tested should always be adjusted carefully by means of the filament rheostat and read on the filament voltmeter. The recommended values for filament voltages and currents may be obtained from the general tube characteristic chart in this chapter. This chart will also supply information as to the normal voltages and corresponding currents for the other elements of the tube. This information is very helpful in selecting the proper meter ranges to be used for the particular type of tube whose characteristics are to be taken. The double-pole double-throw switch in the grid circuit makes it possible to change the polarity of the grid without the necessity for changing the meter E_g connection.

Switches S-1, S-2 and S-3 in the grid, screen and plate-battery circuits enable these circuits to be opened when the instrument is not in use, to avoid continuous discharge of the batteries through the voltage adjusting potentiometers P-1, P-2 and P-3. These may be in the form of locking push switches in order that they may be closed at the time the test is made, but may be readily released upon completion of reading of the meters. Potentiometers P-1, P-2 and P-3 should be well constructed with well designed sliding contact arms, to enable accurate grid screen and plate voltage settings to be obtained. They simply apply to the test circuits a certain definite proportion of the total fall of potential in the potentiometer resistance caused by the flow of the battery current through it ($E=I\times R$) in each case. By varying the position of the sliding contact, any voltage between zero and the maximum p.d. of the battery may be applied to the test circuit. Potentiometers are used extensively for this purpose.

In the pentode tube, since the cathode or suppressor grid is already connected to the cathode or filament inside of the tube, no external connections need be made to it.

279. Grid potential-plate current curves: The data necessary for drawing the grid potential-plate current curves of a tube may be obtained by means of the apparatus of Fig. 199 as follows:

Experiment: Arrange the apparatus as shown, making tests on several common types of tubes. Set the filament current at the proper normal value recommended by the manufacturers, (see V. T. Characteristic Chart in Fig. 214). Set the plate voltage at a fixed value of say 22.5 volts, and take readings of the plate current and grid potential for every step, as the grid potential is varied in steps of one volt, from a point where the plate current is zero, to a positive grid potential of about 10 or 15 volts. Throwing the D.P.D.T. switch to the right makes the grid *positive*. The connections of the grid voltage meter E_g do not have to be reversed. Then set the plate voltage at a higher fixed value of say 90 volts and repeat. Take the readings for several fixed plate voltage values in this way, up to the maximum rated plate voltage of the tube, and plot the readings to enable you to draw E_g — I_p (grid potential-plate current) curves, like those at (A) in Fig. 200. The student should learn the standard abbreviations and letter symbols for plate voltage, plate current, etc., used in radio work. These are listed in Appendix B at the back of this book.

The family of E_g — I_p curves shown at (A) of Fig. 200 are those for a 227 type tube. They reveal several interesting and important facts. At the large negative grid potentials, there is little or no current flowing in the plate circuit, since the strong negative charge on the grid repels almost all of the electrons back to the cathode, practically none of them getting through the spaces between the grid wires. As the negative grid potential is decreased, some of the electrons get through the openings in the grid and the space charge and the plate current begins to increase at a slow rate at first, then more rapidly, and finally in a steep straight line. If the readings were carried out with positive grid potentials large enough, the curves would finally flatten out horizontally when all of the

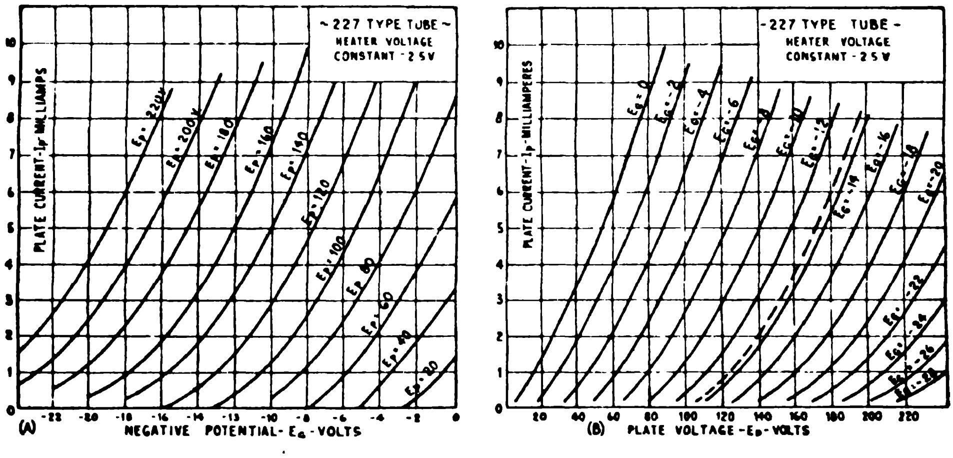


Fig 200—Left Family of Eg-Ip curves for a '27 type vacuum tube.
Right Family of Ep-Ip curves for a '27 type vacuum tube

electrons given off by the filament at that particular temperature are drawn over to the plate as fast as they are emitted (saturation).

If the plate voltage is now increased, and the test repeated with various grid potentials again, a new curve is produced which is to the left of the one just drawn, but practically parallel to it. The data for

higher plate voltages will result in several other curves as shown. This is called a "family" of curves and gives us important information about the effect of the grid potential upon the plate current at various fixed values of the plate voltage.

If a microammeter were connected in the grid circuit during the test, it would show that a very small current was flowing in the grid circuit. The grid current curve for a 201A tube is shown at the lower right of Fig. 197. In all applications of the vacuum tube as an amplifier, the grid is kept at a high negative potential in order to keep the grid current as low as possible to prevent distortion as we shall see later, in Art. 340.

280. Plate voltage-plate current curves: The effect of the plate voltage upon the plate current (grid potential kept constant) may be seen from the curves at (B) of Fig. 200. The data for these is obtained as follows, by means of the same apparatus:

Experiment: Set the grid potential fixed at some value, say 4.5 volts for an ordinary receiving tube, and read and record the plate current and plate voltage for each step, as the plate voltage is increased in steps of about 20 volts at a time, from zero to the maximum rated plate voltage of the tube. Then change the grid potential to 10 volts negative and repeat the readings; then at 15, 20 volts negative, etc. The readings for a 227 type tube are plotted at (B). Note: This data may also be obtained directly from the curves at (A) by locating on the curves the proper values of plate and grid voltages and projecting across to the current scale to find the corresponding plate currents.

The E_p — I_p curves at (B) show that the plate current increases as the plate voltage is increased, and as the grid potential is increased toward positive. The curves are practically parallel over their straight parts, as shown.

The curves of (A) and (B) enable us to calculate all of the constants of the tube, and also help us to foretell the behavior of the tube when it is connected into circuits with other apparatus of known electrical constants. They are of great value, in that they tell us a great deal about the characteristics of a radio tube at a glance. The general grid voltage-plate current curves for most tubes resembles those shown in (A) of Fig. 200, although the numerical values of grid voltage and plate current will vary with the different types of tubes and different plate voltages.

281. Vacuum tube notation: A very useful shorthand method of designating the various important factors affecting the operation of vacuum tubes is in common use and the student is urged to learn and use these expressions in his work. The designation for plate voltage is E_p, for filament voltage E_f, for grid voltage E_g. Similarly, plate current is usually written as I_p, filament current is I_f, and grid current is I_g. The subscript in each case indicates whether the quantity refers to the grid, plate, or filament circuit. A complete list of these abbreviations will be found in Appendix B at the back of this book. Other abbreviations will be mentioned as we proceed with our study.

282. Vacuum tube constants: Every tube has certain constants and characteristics which indicate its value either as a detector, audio frequency amplifier, radio frequency amplifier or oscillator. The ***constants***

are, the amplification factor, the d-c plate resistance, plate impedance, the mutual conductance and plate-to-grid internal capacity. The important *characteristics* are, the grid voltage-plate current curve, and the plate voltage-plate current curve. We have studied how to find the important characteristics, and will now proceed to a study of how the constants are determined.

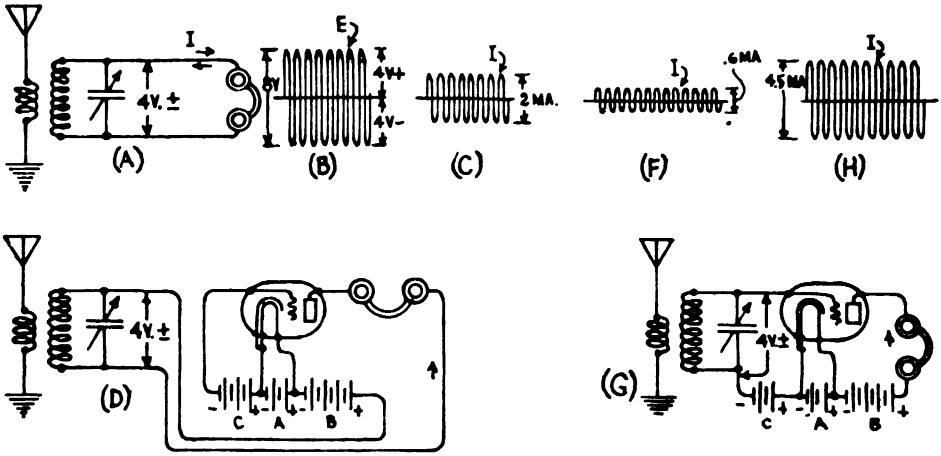


Fig 201—Various methods of applying signal voltage to a vacuum tube circuit; variations produced in the plate current in each case

283. What amplification factor means: The amplification factor is one of the most important constants of a tube, for the usefulness of a tube as an amplifier depends a great deal, but not entirely, on it. Let us study the action of the vacuum tube very carefully in order to see just what this important factor really means. First let us see why we use vacuum tubes as amplifiers anyway, and why we connect them as we do.

All practical forms of earphones and loud speakers in common use depend for their operation upon the fact that a varying current sent through their actuating windings produces motion of the diaphragm,—resulting in sound waves. It is the amplitude of the *variations* in the current, not the *total amplitude* of the current itself (see Article 251), which determines how great the amplitude of the vibrations of the speaker diaphragm are, and how loud the resulting sound will be. Remember this fact for it is important. Now let us refer to the simple receiving circuit shown at (A) of Fig. 201.

For simplicity in our discussion we are going to overlook several technicalities which will not affect the tube action. First, we will eliminate the detector and consider that we may feed the alternating signal voltage appearing across the terminals of the tuning circuit, directly to the winding of a pair of standard earphones or a

loud speaker having an impedance of 4000 ohms. Also we will assume that the signal voltage appearing across the tuned circuit has a peak amplitude of four volts in each direction, that is, it varies from zero to four volts during each half of a r-f signal cycle, first in one direction and then in the other. Furthermore, for convenience, we will suppose it is of simple sine-wave form as shown at (B) .

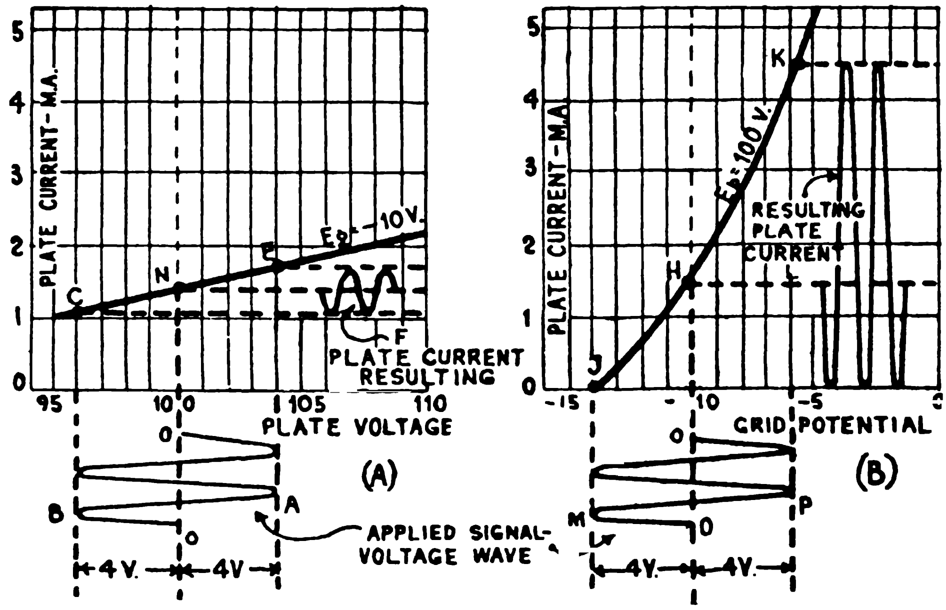


Fig 202—Graphs showing the actual plate current variations caused by introducing the signal potential into (A) the plate circuit of a tube (B) the grid circuit

Under the conditions mentioned above, at the instant that the maximum peak voltage is applied to the earphone or speaker winding each cycle, the current through it will simply be equal to $I=E\div Z$ or $I=4\div 4000$ ohms $=$ .001 ampere or one milliampere. The current therefore varies as shown at (C) between the values of 0 and 1 milliampere in each direction for each cycle, making a total variation of 2 m.a. The speaker diaphragm will move back and forth a certain amount due to this and a certain volume of sound will be produced. This would be one way of operating the receiver.

Now let us suppose that the signal voltage were introduced in the plate circuit of say a 3-electrode vacuum tube instead, as shown at (D), with the earphones in series so the plate current of the tube flows through them. Let us assume that the tube is being operated at normal filament voltage and that the applied steady plate voltage is 100 volts and a steady grid potential of minus 10 volts is supplied by the C battery. Then during each half cycle, the a-c signal voltage introduced will be in the same direction as that of the applied tube plate voltage and will add to it, making it 100 + 4 or 104 volts. During the next half cycle it opposes it, making the net voltage actually applied to the plate equal to 100 − 4 = 96 volts. Thus the *effective* plate voltage varies between 96 and 104 volts during each cycle. In order to see just what effect this has, let us refer to (A) of Fig. 202 which represents the single characteristic curve of this vacuum tube for the operating conditions under which it is working, i.e., a steady grid potential of minus 10 volts supplied by the C battery. The no-signal condition is represented by point N. The signal voltage curve is drawn at the bottom about the axis O—O which represents the normal plate voltage of 100 volts. When the signal voltage goes to four volts in the direction opposite to that of the plate

voltage, as represented by point B, the effective plate voltage becomes 96 volts and by projecting up on the E_p — I_p curve we find that at this voltage the plate current flowing through the tube and earphones is 1.1 milliamperes, represented by C. On the next half cycle, the signal voltage is 4 volts in the opposite direction, as at point A, adding to the plate voltage and making the effective plate voltage 104 volts as represented by point E on the curve. The plate current now flowing as represented by this point on the curve is 1.7 milliamperes. Therefore the plate current flowing through the earphones varies between 1.1 and 1.7 milliamperes about the normal value of 1.4 m.a., or a total variation of 0.6 milliamperes during each cycle, as shown at (F) of Fig. 201. The plate current flow is represented by curve F. This is constructed by projecting several points from the E_p sine wave up to the characteristic curve and then projecting over to the right. The plate current always flows in the same direction in the plate circuit, i.e., it is a unidirectional pulsating current, it merely varies up and down from the normal no-signal value of 1.4 m.a. represented by point N. The variation of the earphone current is now only 0.6 m.a. each way as against the 2 milliampere variation obtained by the arrangement of (A) of Fig. 201. Obviously, the signal will not sound as loud as before, so we have failed to gain anything by the use of the tube in this way, but have actually lost some volume.

Let us now see what happens if we introduce this same alternating signal voltage of 4 volts into the grid circuit of the vacuum tube, as shown at (G) of Fig. 201. The plate voltage now remains steady at 100 volts and the steady C bias voltage is 10 volts negative as represented by point H on the E_g — I_p characteristic curve of the tube shown at (B) of Fig. 202. This is the characteristic for a plate voltage of 100 volts. When the signal voltage is maximum in the same direction as that of the C battery voltage (point M), it adds to it and thereby swings the grid potential to $10 + 4 = 14$ volts negative. When it is maximum in the opposite direction (point P) the net grid potential is $10 - 4 = 6$ volts negative. Obviously, the a-c signal voltage results in making the potential of the grid swing alternately 4 volts above and 4 volts below the steady negative voltage of 10 volts supplied by the C battery, during each cycle, that is, the grid potential varies between minus 6 and minus 14 volts as shown by points J and K on the characteristic curve. When the grid is at minus 6 volts, the plate current is found to be 4.5 milliamperes. When it swings to minus 14 volts, the plate current is practically zero. Therefore, while the signal goes through each cycle, the plate current of the tube flowing through the earphone or loudspeaker winding now varies between 0 and 4.5 m.a. and the sound it produces is proportional to this, a total variation of 4.5 m.a. as shown at (H) of Fig. 201 and L of Fig. 202. Comparing this with the 0.6 m.a. variation produced when the same signal was introduced into the plate circuit, we can see that the signal is made much more effective by introducing it into the grid circuit. The comparitive plate current changes may be seen directly from the height of the plate current curves F and L of Fig. 202. Since the signal-voltage wave-form and the plate current scale have been drawn the same in each case, the amplitude of curves F and L may be compared directly. How much more effective this is, may be found by dividing

$$\frac{\text{plate current change produced by the given grid potential change}}{\text{plate current change produced by an equal plate voltage change.}}$$

For our case, this gives $\frac{4.5}{0.6} = 7.5$. This is called the *amplification factor* or constant of the tube.

Perhaps you now have a clear idea of the reason why we always introduce the signal voltage into the grid circuit of a vacuum tube rather than into any of the other circuits, and also, what is meant by the amplification constant or factor of a tube. If we want to consider the effect of the tube alone, we can look at amplification factor in another way as follows:

In the normal use of a vacuum tube as an amplifier, we desire to produce as large a change in plate current by means of the signals as possible. The plate circuit of a tube (A) in Fig. 203 is a complete electrical circuit as shown at (B), and somewhat similar to the ordinary electrical circuit at (C). It has in it, a source of voltage represented by the B battery or other B supply device, in series with the impedance of

whatever device is connected in its plate circuit. This is analogous to the simple electrical circuit shown at (C). In this circuit, there are two ways of producing a change in the amount of current flowing,—either by increasing or decreasing the applied voltage E, or by increasing or decreasing the resistance R of the circuit. In our tube circuit at (B), we can also change the amount of current flowing in the plate circuit in either of two ways. First, we may increase or decrease the plate voltage. Second, we may increase or decrease the resistance of the path from plate to cathode, shown in dotted lines at (B), by increasing or decreasing the potential applied to the grid and thus varying the number of electrons in the space. Now either of these will cause a change in plate current, but a change of say 5 volts in the plate voltage will cause only a slight change in plate current, whereas a change of 5 volts in the potential applied to the grid of the tube will cause a very much larger change in the plate current because the grid being much nearer to the cathode (source of electrons) than the plate is, can control their flow more effectively. For instance, in a tube having an amplification factor of 9, let us suppose that a 5 volt change in the grid potential

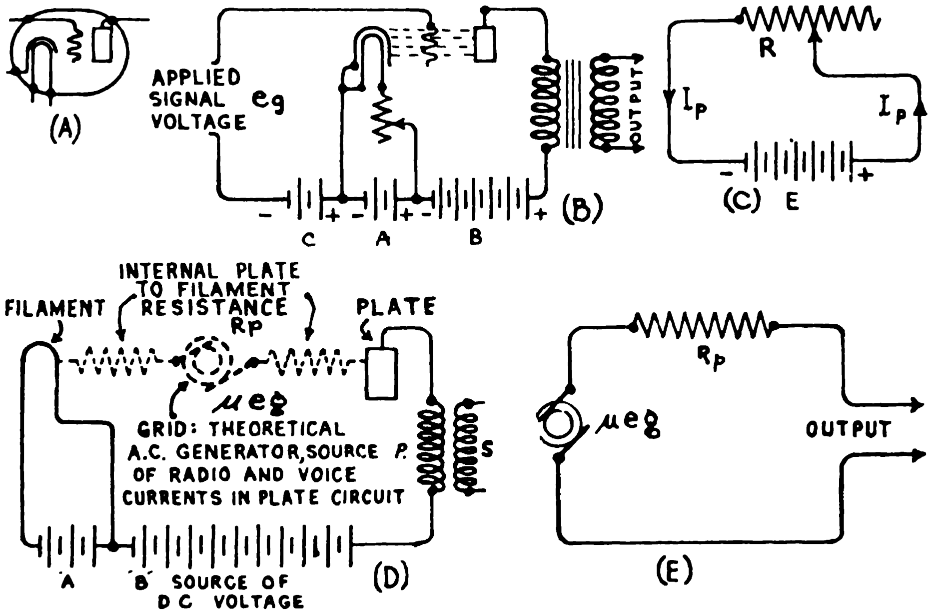


Fig 203—The action of the plate circuit of a vacuum tube as a variable resistor

causes a change of 10 milliamperes in the plate current. Were we to change the plate voltage sufficiently to bring about the same change of plate current (keeping the grid potential constant) we would find that it would require a 5 $\times$ 9 = 45 volt change of plate voltage to do it. Thus, for this tube, a change of grid potential is 9 times as effective in varying the plate current as a similar change in plate voltage is. The ratio of the two is a measure of the amplification effect or factor of the grid potential in producing plate current changes.

That is, the *amplification factor* of the tube is equal to:

$$u = \frac{\text{effect of grid potential in controlling the plate current}}{\text{effect of plate voltage in controlling the plate current.}}$$

Since amplification factor is a rather cumbersome word to write, the abbreviation "mu" or the Greek letter μ is commonly used as the abbreviation for it. Thus,

$$u = \frac{\text{plate voltage change required to produce a given plate current change}}{\text{grid potential change required to produce the same plate current change.}}$$

In the case considered in Fig. 202, the amplification factor of the 227 type of tube used is $\mu = \frac{4.5}{0.6} = 7.5$. This checks fairly well with the value of 9 given for a 227 type tube in the table of vacuum tube characteristics in Fig. 214.

The amplification factor of vacuum tubes is very important, especially if the tube is to be used as an amplifier or oscillator. In this case, it would seem that the mu should be as high as possible, but there are other considerations, such as plate impedance, etc., which determine the usefulness of a tube when used in actual circuits, as we shall see. The amplification factors of different types of tubes in common use vary between rather wide limits. Thus the mu of a 171A tube is about 3, whereas that of a 224 screen grid tube is about 420. The student should refer to the vacuum tube characteristic chart in Fig. 214 and glance down the column marked "voltage amplification factor". This will give a good idea of the values of mu for the various tubes. We shall see in the next chapter that the mu of a given tube is controlled largely by its mechanical construction, and the relative distances between the grid and cathode and the plate and cathode. A closely wound grid mounted close to the cathode produces a high amplification factor, one with a wide mesh and not so close to the filament produces a tube with a low amplification factor. Also, in screen grid tubes, mu is increased by the action of the screen grid, which neutralizes the effect of the space charge between the cathode and plate as we shall see later. The actual voltage amplification or increase of voltage realized in a practical amplifying circuit depends not only on the mu of the tube but also on the resistance, the inductance, and the capacitance in the plate circuit of the tube. The amplification factor of a given tube does not vary much under the conditions under which the tube is ordinarily used, except in the case of the variable-mu tube. The methods of measuring the mu of vacuum tubes will be considered in Articles 288 and 289.

284. Simplified equivalent tube circuit: In most all radio work, we are concerned with vacuum tubes only in connection with alternating currents or voltages of some form. Radio receivers employ tubes as amplifiers of the weak radio-frequency voltages induced in the receiving antenna circuit by the passing radio fields. Tubes are also used to amplify the low-frequency alternating voltages encountered in the audio circuits after the detector. Some tubes are utilized as rectifiers of the 60-cycle power current, while others function as rectifiers of the signal currents. The first are called rectifiers and the second, detectors. Under any circumstance, we will always be considering the applied voltages on the grid resulting from some form of alternating voltage. In other words, the grid voltages, with which we will be concerned in making a study of the "mu" of the tube, will always be alternating voltages.

To simplify the visualization of the tube action in associated electric circuits, engineers prefer to consider the schematic circuit diagram of a vacuum tube as shown at (D) of Fig. 203. Here the grid circuit is replaced by a small a-c generator directly in the plate circuit. The voltage

of this schematic generator is the voltage of the a-c signal impulse on the grid multiplied by the mu of the tube, because any change in voltage in the grid circuit has the same effect on the plate current as a voltage "mu" times as large introduced directly in the plate circuit. Therefore if we are to consider our grid voltages as acting directly in the plate circuit, we must consider them as being "mu" times as large as they really are. The internal resistance of this generator is equal to the plate-to-cathode resistance of the tube. This arrangement reduces the complicated circuit of the tube shown at (B) to a simple equivalent series plate circuit with an equivalent a-c generator whose voltage is μe_g, representing the effect of the grid control on the plate current. The diagram at (D) may be further simplified as shown at (E). The tube is considered this way in all problems. The voltage of this hypothetical generator would be high in a high-mu tube and low in a low-mu tube.

285. D-C plate resistance of a tube: In the simple electrical circuit of (C) in Fig. 203 a certain direct current flows through resistor R due to the applied voltage E. Likewise in a vacuum tube a certain steady d-c plate current I_p flows across through the space between the plate and cathode (actually it is the electrons flowing in the opposite direction) and around through the circuit, due to the electrical pressure of the applied, d-c plate voltage E_p. Applying ohm's law, we find that the d-c resistance of the space between the plate and cathode is:

$$R = \frac{E_p}{I_p}$$

This is called the *d.c. plate resistance* of the tube. The electrical power used up by the flow of the plate current through the resistance of this path is $W = E_p \times I_p$ or $\frac{E_p^2}{R}$ or $I_p^2 R$.

This power is the rate at which kinetic energy is given up by the electrons when they strike the plate at their high velocity after being pulled to the plate by the attractive force of its positive charge. When each electron hits the plate, its kinetic energy due to its motion is given up, and the energy thus released at the plate by all of these electrons produces heat which may heat the plate to red heat unless it is designed to have a large enough surface to dissipate the heat. This action is similar to the heat which would be produced in a large steel plate if a shower of bullets from a machine gun were made to impinge upon its surface continuously. The kinetic energy of the motion of every bullet would be transformed into heat as soon as it was stopped suddenly by the surface of the steel plate. The heat would result in raising the temperature of the plate. We shall see later that these bombarding electrons also cause secondary emission of electrons from the plate, the secondary emission electrons interfering with the normal flow of those from the cathode. The action of electron bombardment may be seen by operating an ordinary tube for

a few minutes with a plate voltage about twice as high as that recommended by the manufacturer. The plate will become red hot. The d-c plate *resistance* is not to be confused with the more important factor which is ordinarily referred to as the a-c *plate resistance* or *plate impedance* of a tube.

286. A-C plate resistance, or plate impedance of a tube: Since we are always interested in the changes produced in the plate current of a vacuum tube in actual operation, it is more important for us to know what the ratio between a *change* in plate voltage and the corresponding *change* in plate current produced by this change in plate voltage is. This is called the *a-c plate resistance* or the *plate impedance* R_p, of the tube and is numerically equal to:

$$R_p = \frac{\text{change in plate voltage}}{\text{change produced in the plate current.}}$$

The a-c plate resistance is the opposition offered to the flow of varying currents in the plate circuit and is not the same as the resistance offered to the flow of a steady d-c current from the "B" battery. The d-c plate resistance governs the steady plate current flow when no signal voltage is being applied to the grid, i.e., the grid voltage is steady. The a-c plate resistance governs the varying plate current flow when a varying signal voltage is applied to the grid, hence it is the more important of the two.

For instance, in (A) of Fig. 202, when the tube considered had a negative grid potential of 10 volts and a plate voltage of 100 volts applied (point N), the steady plate current flowing was 1.4 m.a. or .0014 amperes. Therefore the *d-c plate resistance* of this tube under these conditions is given by $R = \frac{E_p}{I_p} = \frac{100}{.0014} = 71{,}000$ ohms (approximately).

However, when the plate voltage was varied from 96 volts (point C) to 104 volts (point E), the plate current changed correspondingly from 1.1 m.a. (point C) to 1.7 m.a. (point E), a net change of 1.7 — 1.1 or 0.6 m.a. Therefore the a-c plate resistance is equal to:

$$R_p = \frac{104-96}{.0017 - .0011} = 13{,}300 \text{ ohms. (approximately)}$$

(1.7 m.a. equals .0017 amperes and 1.1 m.a. equals .0011 amperes.)

The d-c plate resistance and the a-c plate resistance both change with changes in plate and grid voltages, so the values of both must be specified when these constants are considered. Thus a 227 tube has an a-c plate resistance of 11,000 ohms at a plate voltage of 90 volts and negative grid potential of 6 volts. When the plate is at 180 volts and the grid is at 13.5 volts negative, the a-c plate resistance is 9,000 ohms. At the conditions mentioned in the problem above ($E_p = 100$ volts and $E_g = -10$ volts) the a-c plate resistance was found to be 13,300 ohms. As the a-c plate resistance varies with each change in plate and grid voltage, it should

be considered only for small voltage changes and at the point on the characteristic curves where the tube is actually operating. The a-c plate resistance depends on the plate-filament spacing and the plate voltage used, the grid voltage, the fineness of the grid mesh, and to a small extent on the distance between the grid and plate. The methods of obtaining and measuring these constants will be taken up in Articles 288 and 289.

287. Mutual conductance: The essential function of an amplifying tube is to produce as large an undistorted change in plate current as possible for a small change in signal potential applied to the grid circuit. As this important property of the tube depends on how much plate current change is caused by a given grid potential change, by comparing these values we obtain a figure of merit which is known as the *mutual conductance*, represented by the symbol G_m. This ratio has been called mutual because it expresses a relationship between a quantity pertaining to the plate circuit and a related quantity pertaining to the grid circuit. It is called *conductance* because it is the ratio of a current to a voltage. (The conductance of a conductor in mhos is defined as "one divided by the resistance in ohms".) Thus:

$$G_m = \frac{\text{change in plate current produced}}{\text{change in grid potential producing it.}}$$

In general, the ratio of the change in current in the circuit of an electrode to the change in the voltage in another electrode is known as the *transconductance*. The term transconductance is also commonly used in radio engineering literature to represent what we commonly refer to as mutual conductance, so it should be remembered.

Thus in the tube whose $E_g - I_p$ curve (for a plate voltage of 100 volts) is shown at (B) of Fig. 202 a change of plate current from 0 to 4.5 milliamperes (point J to K) was produced by a change in applied grid voltage from 14 to 6 volts negative. This represents a change of 4.5 m.a. or .0045 amperes in plate current, produced by a change of 8 volts in grid potential. Thus

$$G_m = \frac{.0045}{8} = .00056 \text{ mhos or } 560 \text{ micromhos.}$$

The mutual conductance is also defined by the ratio between the amplification factor and the plate resistance, because

$$\mu = \frac{\text{plate voltage change}}{\text{grid potential change}} \qquad (1)$$

$$R_p = \frac{\text{plate voltage change}}{\text{plate current change}} \qquad (2)$$

Therefore $\frac{\mu}{R_p}$ is equal to expression (1) divided by expression (2) from which we obtain finally after cancelling out the numerators of (1) and (2) $\frac{\mu}{R_p} = \frac{\text{plate current change}}{\text{grid potential change}}$; but according to the defini-

tion given above, this expression is equal to the mutual conductance. Therefore: $G_m = \frac{\mu}{R_p}$. Also, $\mu = G_m \times R_p$, and $R_p = \frac{\mu}{G_m}$

In general, the higher the mutual conductance of a tube, the more efficient it is considered to be as an amplifier, but comparison should only be made between tubes *designed for the same service* and having similar characteristics.

For example, the 227 type tube designed for general amplification use has a mutual conductance of 1,000 micromhos at 135 volts plate voltage, and the 120 type tube which is designed entirely for output service has a mutual conductance of 525 micromhos at the same plate voltage. The latter tube, nevertheless is capable of handling 110 milli-

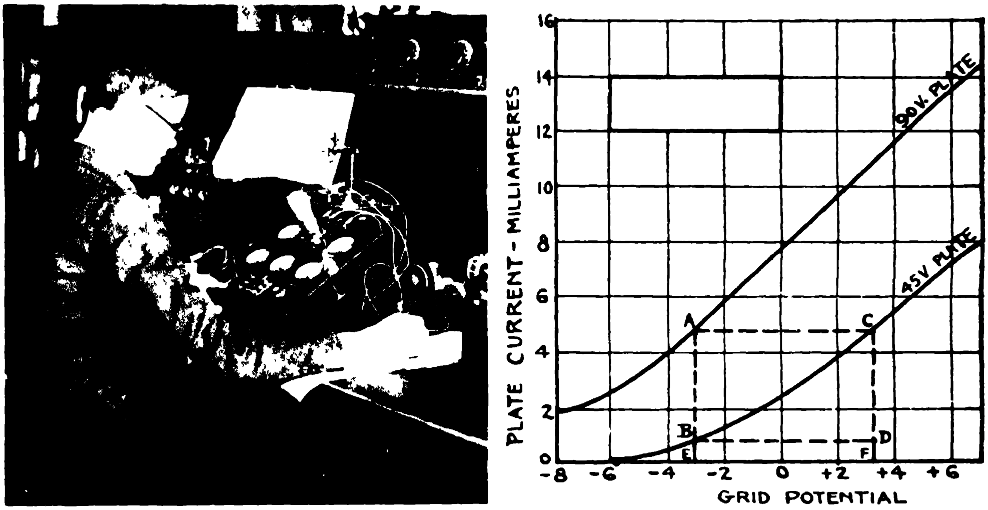


Fig. 204—Left: Laboratory type tube tester for taking tube characteristics.
Right: How mu is determined from the Eg-Ip characteristic curves for two values of plate voltage.

watts of undistorted power output when sufficient input voltage is available and the load is properly adjusted, against an undistorted power output of 80 milliwatts for the 227 tube.

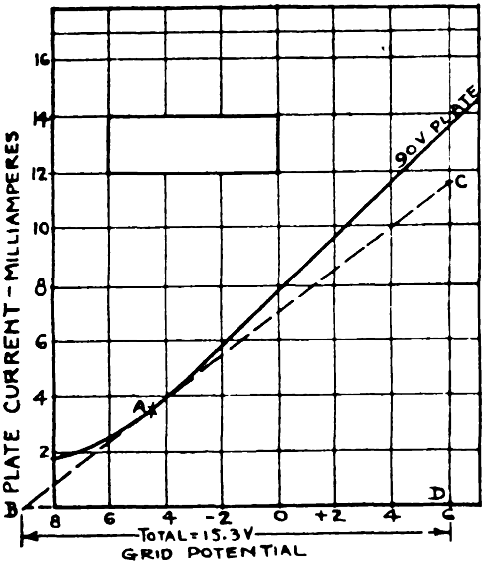
When one is considering two tubes of the same type, the one with the higher mutual conductance is the better one, but rather large differences in mutual conductance may occur before any difference in the operation of the circuit in which the tubes are used will be noticeable. The mutual conductance is really the best tube factor on which to compare tubes which are to be used for the same purpose. Its measurement is considered in Articles 288 to 290. Since the mutual conductance depends on the plate resistance, it varies with the plate voltage, and therefore mutual conductance values are meaningless unless the voltages applied during the measurements are specified.

288. Obtaining tube constants from curves: In laboratory work where the performance of vacuum tubes is to be analyzed, the various con-

stants may be obtained from the E_p - I_p and the E_g - I_p curves which are drawn from the readings taken on tube testing apparatus of the type shown in Fig. 199. The actual tube tester in operation is shown in the photograph at the left of Fig. 204.

To show the method employed for finding the *amplification factor* ("mu") from the E_g - I_p characteristic curves of a vacuum tube; consider the typical amplifier tube curves shown at the right of Fig. 204. One is for a steady plate voltage of 45 volts and the other is for 90 volts.

Selecting any point B on the straight portion of the 45 volt curve, drawn a vertical line A B E through this point, and a horizontal line A C, through intersection point A with the 90 volt curve, to the 45 volt curve and BD through point B. Drop a



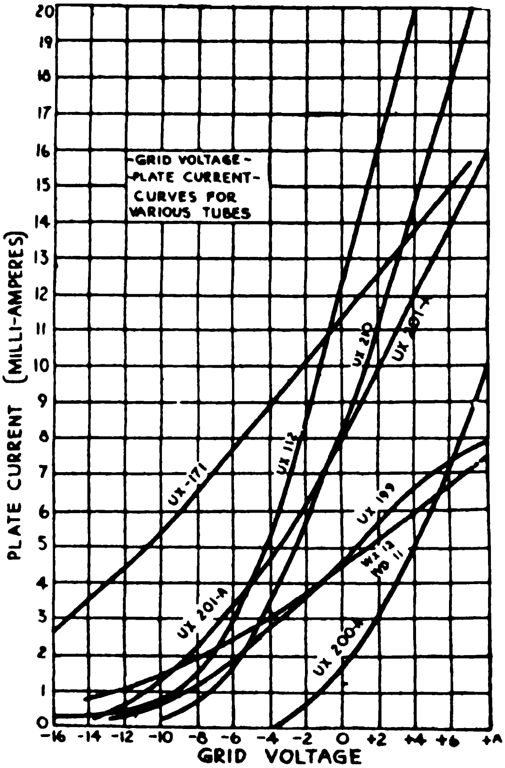


Fig. 205—Left: Method of finding mutual conductance from the Eg-Ip characteristic.

Right: Grid voltage-plate current characteristics of some commonly used tubes

perpendicular line from intersection point C, to F. Now consider the tube operating at the lower plate potential of 45 volts and grid potential equivalent to point B on its characteristic curve.

If the grid potential is increased an amount equal to E F (or BD) units, the operating point moves to C, and the plate current has increased an amount C-D. This same increase C-D in plate current would also result if the grid potential were kept at value E and the plate voltage were increased from 45 to 90 volts to point A. Therefor, an increase of E-F units of grid potential has the same effect on the plate current as an increase of 45 volts in plate potential. From the foregoing definition of amplification factor, then the mu of this tube is 90 volts minus 45 volts divided by E-F (6.3 volts), or mu=7.1. That is, the grid potential exerts 7.1 times as much influence upon the plate current as does the plate voltage itself at the particular operating point B.

The methods for finding the d-c plate resistance and the a-c plate resistance for any particular operating condition have already been explained in Article 286. Since the mutual conductance is equal to the change in plate current divided by the change in grid potential producing it, it is found by merely measuring the *slope* of the E_g - I_p characteristic curve for the plate voltage at which the tube is operating. As the characteristic curve is not a straight line, its slope or "slant" changes for different values of E_g and E_p, (different points on the curve, see left of Fig. 205). Therefore, it must be taken at the point on the curve representing the particular value of grid potential applied to the tube.

Thus let it be desired to find the mutual conductance of the vacuum tube whose E_g - I_p characteristic curve is shown at the left of Fig. 205, when the tube is operating with a plate voltage of 90 volts and a negative grid potential of 4.5 volts. This operating condition is represented by point A on the curve. The slope of the curve is found by drawing a tangent line BC to it at the point considered as shown, and then forming a triangle BCD. The vertical height CD of the triangle divided by the total base line, BD (adding positive and negative grid potentials together to get the total length of BD), is equal to the slope of the curve at the point A.

Therefore to find the slope of the curve at point A, lay a straight-edge tangent to the curve at the point A, and draw tangent line B C so it cuts the horizontal axis. At any point C draw the perpendicular line C D; now measure the ordinate C D of the point of intersection (say 11.6 milliamperes or .0116 amperes). Also measure the horizontal distance B D from this latter point to the point where the tangent line intersects the horizontal axis. (Say a total of 15.3 volts.) Dividing the former distance .0116 amp. by the latter 15.3 volts, gives the slope of the curve or the mutual conductance at point A, which in this case is .00075 mhos or 750 micromhos (the micromho is the unit of conductance ordinarily used in vacuum tube work).

At the right of Fig. 205, the grid potential-plate current characteristics of various commonly used vacuum tubes are shown plotted on the same axes. The steeper the curve, the higher is the amplification constant.

The curves at the left of Fig. 206 show how the constants of a typical 3-electrode amplifier tube vary for different values of grid potential. Those at the right show how the constants vary for various values of plate voltage. Notice that the amplification factor is practically constant, but that the mutual conductance and plate impedance vary over rather wide limits. Hence the necessity for specifying the plate and grid voltages when speaking of either of these two constants for a tube. An idea of the values for various types of tubes may be obtained from inspection of the proper columns in the vacuum tube characteristic table of Fig. 214.

289. Measuring tube constants quickly: The important tube constants μ, R_p and G_m which define all of the tube's characteristics, may be found from the plotted characteristic curves of the tubes as explained in the previous article, but this is a slow laborious process since all of the readings for plotting these curves must be taken and plotted, and finally the constructions and computations just mentioned must be made. Obviously such a procedure does not lend itself to the sort of rapid testing required in production work. There are simpler methods of finding these constants by means of a simple circuit arrangement as shown at the left of Fig. 197, and there are also special testing devices for measuring them

directly. The latter will be studied in Art. 295. A simplified method of measuring the *mutual conductance* is as follows:

Place the tube in the tester, set the filament voltage at the correct value and set the plate voltage at the value at which the tube will operate, say 180 volts. If the grid bias voltage under these operating conditions is to be say, 13.5 volts negative (227 type tube) set the grid voltage at minus 14 and then minus 13 and read the plate currents each time. Assuming that these plate current readings are 4.5 and 5.5 milliamperes respectively, the mutual conductance is found from:

$$G_m = \frac{\text{change in plate current (amps.)}}{\text{change in grid voltage}} = \frac{.0055-.0045}{14-13} = \frac{.001}{1} = .001 \text{ mho. or}$$

1,000 micromhos.

Following is a simple method of measuring the a-c plate resistance (or plate impedance) of a tube:

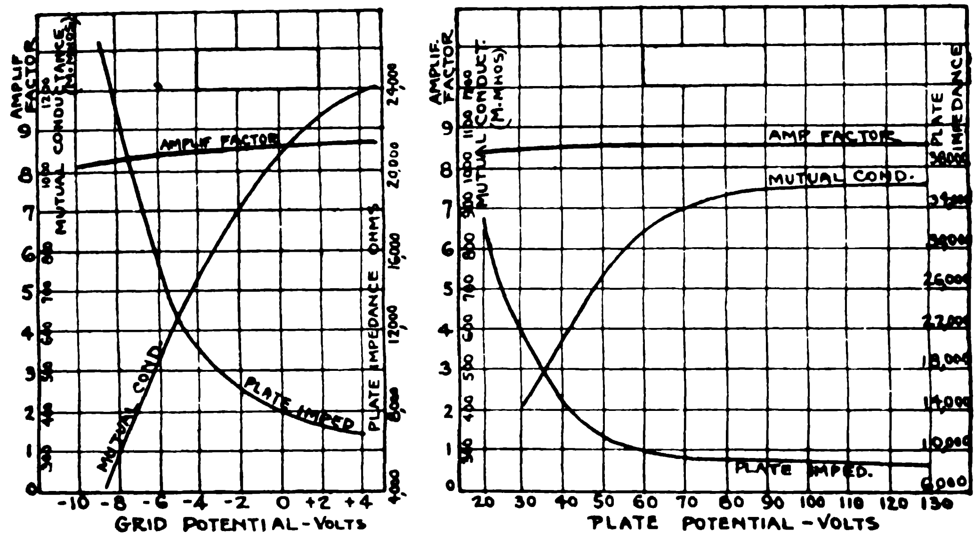


Fig. 206—Left: Curves showing how the mu, Gm, and Rp of a typical 3-electrode tube vary with change of grid potential
Right: How the constants vary with change of plate potential

Set the grid bias voltage at the value desired (for example 13.5 volts negative for a 227 type tube), and choose the value of plate voltage at which the tube will probably operate (say, 180 volts in this case). Then set the plate voltage at a value somewhat higher than this, and read the plate current. Suppose the plate voltage is set at 200 volts and the plate current reading is 8.5 m.a. Now reduce the plate voltage to a value below normal, (say 160 volts) and read the plate current again (say 4 m.a.). Then the a-c plate resistance is:

$$R_p = \frac{\text{change in plate voltage}}{\text{corresponding change in plate current (amp.)}} = \frac{200-160}{.0085-.004} = 9{,}000 \text{ ohms. (approx.)}$$

This means that for this tube at a grid bias voltage of -13.5 volts, the average plate impedance between the values of E=200 and 160 volts is 9,000 ohms.

Following is a simple method for obtaining the *amplification constant.* Set the plate voltage at a certain normal value and read the corresponding plate current. Now change the plate voltage to some other value and read the plate current again. Then adjust the plate current back to the original value of the first condition by varying the grid voltage. Then the ratio of the change in plate voltage required to change the plate current this certain amount, to the change in grid voltage

to produce the same plate current change, is equal to the amplification constant, or,

$$\mu = \frac{\text{first plate voltage} - \text{second plate voltage}}{\text{second grid voltage} - \text{first grid voltage.}}$$

The value of the amplification constant may be calculated directly from the values of mutual conductance and a-c plate resistance found previously, without necessity for another test. Since, $G_m = \frac{\mu}{R_p}$ then $\mu = G_m \times R_p$. Therefore, "mu" can be found simply by multiplying the mutual conductance by the a-c plate resistance.

290. Tube checkers: As explained previously, the three important electrical characteristics of a vacuum tube are its amplification constant, a-c plate resistance, and mutual conductance. It would appear that all three quantities would have to be measured in order to tell whether a tube is in good condition or not. Actually, however, this is not necessary for ordinary rapid service testing. If we can measure one of these factors, we will have a check on the other two, provided we know what the normal characteristics of the particular type of tube being tested should be. The factor usually chosen for measurement in commercial tube checkers, used by radio servicemen and dealers is the mutual conductance, for this is the most important quantity to determine. If a test indicates a tube to have a normal value of mutual conductance we can be reasonably sure that the amplification constant and a-c plate resistance are normal, since if either of these factors were incorrect, the mutual conductance would be affected. Any change due to presence of gas, low electron emission or disarrangment of a tube's electrodes will also alter the mutual conductance. Now in checking the condition of tubes we do not have to actually measure and calculate the mutual conductance—all we need is some indication that the tube has a normal characteristic. The simple relation $G_m = \frac{\text{change in plate current}}{\text{change in grid potential}}$ indicates a method of doing this. Evidently, if we change the grid voltage and note the change which this produces in the plate current, we will have in effect an indication of mutual conductance and from a chart we can determine whether the change in plate current that we noted is normal for the type of tube being tested. This is the basis for the operation of practically all the common tube checkers. The circuit of the tube checker is provided with a switch, (usually operated by a button), which when pressed will change the grid voltage on the tube by about 3 or 4.5 volts. We can calculate, or by measuring a large number of new tubes and averaging the results, determine the change in plate current which should be obtained if the tube is good. A simple chart can then be engraved on the face of the tester which will indicate the plate current readings which should be obtained with normal tubes of the various types. By using such a tube tester, it is therefore possible to obtain for all practical servicing purposes, an accurate, trustworthy indication of how good a particular tube is, and whether or not it should be replaced. Tube checkers are usually arranged to supply the proper filament, plate

and grid voltages to the tube being tested, by means of a suitable transformer operated from the 110 volt a-c electric light line.

Fig. 207 shows the circuit diagram of a tube checker which was originally devised by the E. T. Cunningham Company but which has been further simplified in order to make possible the use of a standard filament heating transformer with a single secondary winding delivering 7.5 volts This has also been altered to make it possible to check all standard types of tubes in use at the present time. A description of this checker follows:

Five sockets are provided for the various types of tubes, two being four prong sockets and the other three being of the five prong type. All of the filament terminals

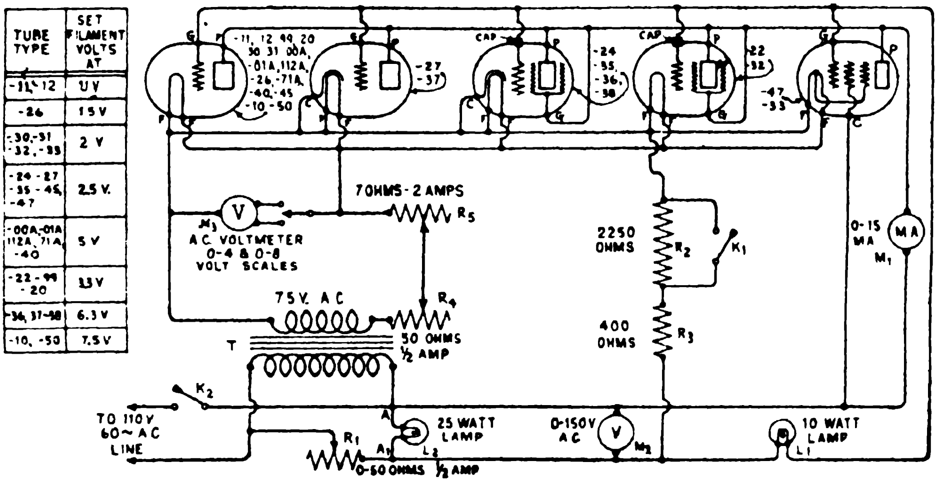


Fig 207—An a-c operated tube checker arranged for rapid checking of the condition of tubes by a rough measurement of the mutual conductance.

of the sockets are connected in parallel across the secondary of the transformer T, having a 110 volt primary and 7.5 volt — 3 ampere secondary. The resistor R_1 in the primary circuit controls the plate voltages applied to the tubes, as read on a-c voltmeter M_2. Filament voltage control is obtained by two series filament rheostats R_4 and R_5 and read on the two-scale a-c voltmeter M_3. R_4 is a high resistance—low current rheostat for adjusting the current when testing a tube which does not require much filament voltage and current. R_5 is a low resistance—high current rheostat for adjusting the current when testing a tube which takes a high filament current. The proper filament voltage settings for the various types of tubes are listed in the table at the left. It is very important to always adjust both rheostats to maximum resistance before inserting a tube in any socket. After the tube is inserted, they may be varied to obtain the proper filament voltage. Because of the voltmeter current, the 50—ohm rheostat R_1 provides all regulation necessary—even for 60 m.a. tubes of the —99 type. Grid bias voltage is obtained from the fall of potential caused by the flow of the plate current of the tube tested through the two resistors R_2 and R_3 connected in one side of the circuit. When K_1 is pressed, it shorts R_2 out of the circuit, reducing the grid bias voltage and thereby causing a change in the plate current.

In operation, the rheostats R_4 and R_5 are first set at maximum resistance value. The tube is then inserted in the proper socket and R_4 and R_5 are adjusted to give the correct filament voltage as shown on meter M_3. Resistance R_1 is then set to make meter M_2 read 100 volts. This insures that the correct filament and plate voltage are

being applied to the tube being tested. The lamp, L_2, across the transformer primary is to reduce the size of the series resistor required for some of the low-filament-consumption tubes and also serves as a pilot lamp to indicate that the checker is turned on. The plate current is then read on M_1 before and after pressing the key K_1. A table of approximate plate current changes to be expected follows:

Tube Type	Average Plate Current Values for Tubes	
	K_1 open	K_1 closed
11	1-1.5	1-2.5
cx-12	1-1.5	2-2.5
26	1.5	4
45	3	11
24	1	2.6
27	1.5-2	3-3.5
99	1.5	3
20	2.5-3	5.5-6
22	2	4-6
01A	1.7	4.5-5.0
40	.7	1.7
71A	3 5-4	12-13
00A	1.5	3.5
10	2	6
50	3	10.5
12A	2	6.5-7.0

These should not be taken as absolute standard values, since slight variations in the values of the biasing resistors, transformer, meter calibration, etc., will cause some changes in the result. It would be best to construct the checker and obtain the plate current changes to be taken as a guide, by actually testing a set of the various types of tubes which are known to be in good operating condition.

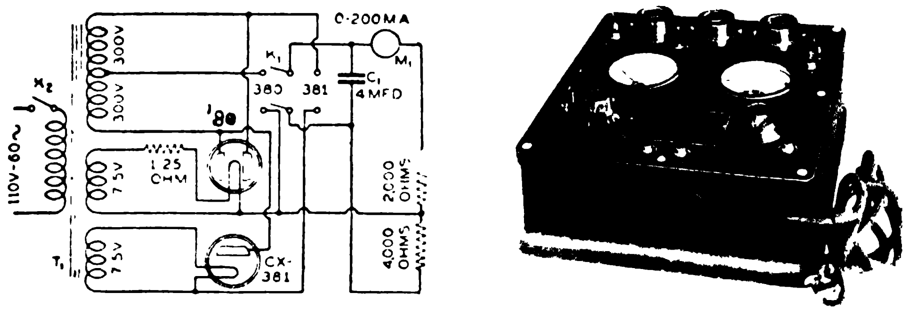
It will be found that the tube readings are dependent on the way in which A and A_1, the plate voltage supply connections, are made to the a-c supply and filament transformers.

These leads should be reversed until the highest readings are obtained, in order to obtain results comparable to this table. The difference is especially noticeable in the case of tubes with a 7.5-volt filament. It is seen that for the screen-grid tubes the screen grid is connected to the plate, making it a three-element tube for purposes of this test. For this reason it is necessary to use a separate socket for screen-grid tubes since on them the control-grid connection is on top and the screen grid is connected to the usual grid terminal of the socket. Clips are provided for connecting to the caps on screen grid tubes. Of course, a-c meters must be used in the checker. The 10-watt 110 volt lamp L_1 used as a protective resistor is included in the circuit to protect the meter in case a shorted tube is accidentally inserted in the socket. A plate-filament or grid-plate short in a tube inserted in this tester will cause the 10-watt lamp L_1, to light and the needle of meter M_1 to vibrate slightly about the zero adjustment, the needle following the 60-cycle current passing through the meter.

A simple checker for quickly checking the condition of half-wave or full-wave rectifier tubes is shown in Fig. 208. If the transformer T used in the tube checker just described also has a 600 volt center-tapped winding and two additional 7.5 volt windings, the rectifier tube checker may be built as part of the former unit using the single transformer to supply all voltages. The rectifier is arranged to operate in a standard rectifier circuit, using the rectifier tube to deliver a current to a fixed load resistance. A low current through this resistance indicates a defective tube.

The circuit shown at the left of Fig. 208 is arranged to use a standard power transformer delivering 600 to 700 volts from a center-tapped high voltage winding and two 7.5 volt windings. A resistance of 1.25 ohms is connected in series with one winding, so that 5 volts appears across the filament of the type '80 rectifier. As can be seen from the circuit diagram, a double-pole, double-throw switch is provided to change from one type of tube to the other. When a type -80 is being tested, it is supplied with 300 volts per plate and it supplies current to a four mfd. condenser and a 2,000 ohm load resistance. When a type -81 tube is to be tested, the switch is thrown to the proper side and this alters the connections so that the tube is supplied with 600 volts on the plate and it feeds into a 4-mfd. condenser and a 6,000-ohm load resistance.

The test is made by simply throwing the switch to the proper position, placing the tube in the proper socket, closing the line switch and reading the milliammeter connected in series with the load resistance. The milliammeter should read 100 ma. or more for a type -80 tube and 60 ma. or more for a type -81 tube. If the power transformer supplies 700 volts across the high voltage secondary, both the readings will be about 10 ma. greater. It is preferable to keep the tube socket terminals beneath



Courtesy Weston Elect Inst Co.

Fig 208—Left: An a-c operated tube checker for checking half-wave or full-wave rectifier tubes.
Right: A typical tube checker for rapidly checking tubes by making a rough measurement of the mutual conductance.

the panel to avoid shocks. A conventional double-pole double-throw tumbler switch should be employed. The 4-mfd. condenser must be a good one capable of working continuously at 1000 volts, d-c. The load resistor must have a high current-carrying capacity.

At the right of Fig. 208 is shown a typical tube checker designed to operate directly from the 110 volt 60 cycle lighting circuit. Variations in line voltage from 90 to 130 volts are compensated by means of the line voltage adjuster mounted on the panel. All a-c or d-c tubes can be tested, including both single and full-wave rectifiers. Both plates of the type 280 tube can be tested by placing the tube in the socket, noting the meter reading and then pressing a button which gives the reading of the other plate. To operate the tester it is necessary to adjust the line voltage regulator until the pointer on the line voltage meter is opposite the arrow. Then the selector switch is set for the proper voltage and the tube inserted in the correct socket. Pressing the button marked "Press for Grid Test" causes the plate current meter reading to change and whether or not the tube is good can then be determined by checking these plate current readings against a chart supplied with the tester.

Set analyzers (which will be described in the chapter on radio set testing and servicing) are also employed for checking the condition of tubes directly in the radio receiver itself, employing the filament and plate voltages from the receiver. By inserting a plug in a given socket and taking the tube out of that socket and inserting it in the set analyzer socket, the tube is tested under its own circuit conditions. Provision is also made in these, for changing the value of grid bias in order to change the plate current and obtain a check on the mutual conductance of the tube.

292. Dynamic characteristics of tubes: All of the characteristic curves and methods of measuring tube constants considered up to this point have been *static characteristics*, that is, they have been based on a steady grid potential and the voltage actually effective on the plate was assumed to be constant. However, this is not what actually happens when tubes are in actual operation, for as vacuum tubes are used in practice in transmitting and receiving circuits, as alternating or pulsating signal e.m.f. is impressed on the grid circuit and results in a pulsating plate current. When some form of coupling device having impedance is connected in the plate circuit of the tube in order to couple it to the next one in an amplifier, the characteristic curve is altered as we shall see. Since vacuum tubes are used mostly in this way, it is necessary for an exact analysis of the tube action to know the shape of the characteristic that obtains when varying signal potentials are impressed on the grid; that is, it is necessary to know the shape of the *dynamic characteristics*. There are three different conditions of operation (1) the dynamic characteristic of the tube itself; (2) that of the plate circuit containing the tube and a non-inductive resistance; (3) that of the circuit containing the tube and an impedance. For the first case the dynamic characteristic coincides with the static characteristic for a range of frequencies up to several hundred thousand cycles per second, so this need not be considered.

293. Tube with resistance output load: In the case where a non-inductive resistance is connected in the plate circuit of a tube, as in the case of a resistance-coupled amplifier, the dynamic characteristic is altered from the static characteristic. Let us refer to the fundamental amplifier circuit shown at (A) of Fig. 209. The source of steady plate voltage supplies a voltage E_b. The plate current I_p flowing through the plate load resistor R_L causes a fall of potential in it equal to $I_p R_L$ volts. As a result, terminal 1 of this resistor is at a lower potential than terminal 2, since the current flows from 2 to 1. Therefore the effective voltage E_p actually existing between the cathode and the plate is less than the applied voltage E_b by an amount equal to the voltage drop in the resistor, or

$$E_p = E_b - (I_p \times R_L)$$

For example, let $R_L = .5$ megohms (500,000 ohms), $E_b = 250$ volts, $I_p = 0.2$ milliampere. Then, $I_p \times R_L = .0002 \times 500{,}000 = 100$ volts and $E_p = 250 - 100 = 150$ volts actually applied to the plate.

Experiment: Connect up a 201-A type tube in the tube tester shown in Fig. 197 with a fixed value of applied "B" voltage of 180 volts and normal filament current. Now measure and plot the plate current as the grid voltage is varied from about 5 volts plus, to 15 volts minus. Repeat this with values of 1,000, 4,000, 10,000, 50,000 ohms connected in series with the plate.

Any variation in the plate current will cause a variation in the I $\times$ R drop across R_L and hence the effective plate voltage E_p will also change according to the equation above. Therefore, any change in the potential on the grid will cause not only a change in plate current, but a variation in effective plate voltage as well, and if the plate load resistor and plate current are large, the effective plate voltage will be quite different from the applied plate voltage. (The values specified for plate voltages in vacuum tube characteristic tables always refer to the actual effective voltage between the cathode and the plate itself.) Therefore the voltage drop

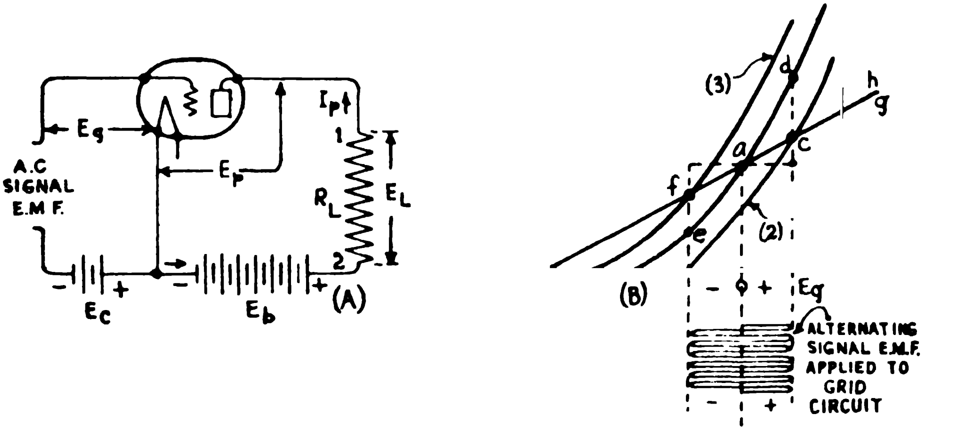


Fig. 209—(A) Vacuum tube with resistance load in plate circuit
(B) Why the dynamic characteristics of a vacuum tube differ from the static characteristics

existing across resistor R_L, (which is the useful voltage to be passed on to the next stage) cannot be determined from the static E_g - I_p characteristic curve, because actually, the effective plate voltage is not constant but changes in instantaneous value with every change of grid potential. Hence the corresponding plate current changes are not exactly what we would expect them to be from a consideration of the static characteristics where the effective voltage actually applied to the plate remains absolutely constant and the plate current changes are due to the grid potential changes alone.

In order to see exactly what happens due to this voltage drop in the plate load resistor, let us consider (B) of Fig. 209. Here the E_g - I_p characteristic curves for three values of effective plate voltage E_p are drawn. These might be simply three of the curves from (A) of Fig. 200. Consider the middle curve to be the characteristic for the condition when the tube has a definite value of effective voltage E_p applied to its plate. The other two are the characteristics for higher and lower values of effective plate voltage. Let the constant grid battery voltage E_c be so adjusted that the direct current in the plate circuit is *oa*. Then, on account of the voltage drop in R_L due to the current *oa* in it the actual effective plate-cathode voltage is

$E_p = E_b - I_p R_L$. If I_p be varied by impressing an alternating potential on the grid, E_p varies accordingly, since the plate-supply voltage E_b is constant. Thus, if a positive wave of signal e.m.f. is applied, the grid potential is shifted toward positive and the plate current increases. This causes E_p to decrease in value, due to the increased voltage drop in R_L, say to the corresponding point on the lower characteristic curve (2) and the current instead of increasing to *d* as it would if E_p remained constant, increases only to *c*. Likewise, when a negative wave of signal e.m.f. is applied, the negative grid potential is made more negative, the plate current decreases only to *f* instead of to *e* as it would if E_p remained constant. The characteristic therefore straightens out and takes the shape given by *fac* instead of *ead*.

The *dynamic characteristic* curves for a typical vacuum tube are shown at (A) of Fig. 210. As the voltage drop through R_L depends on the

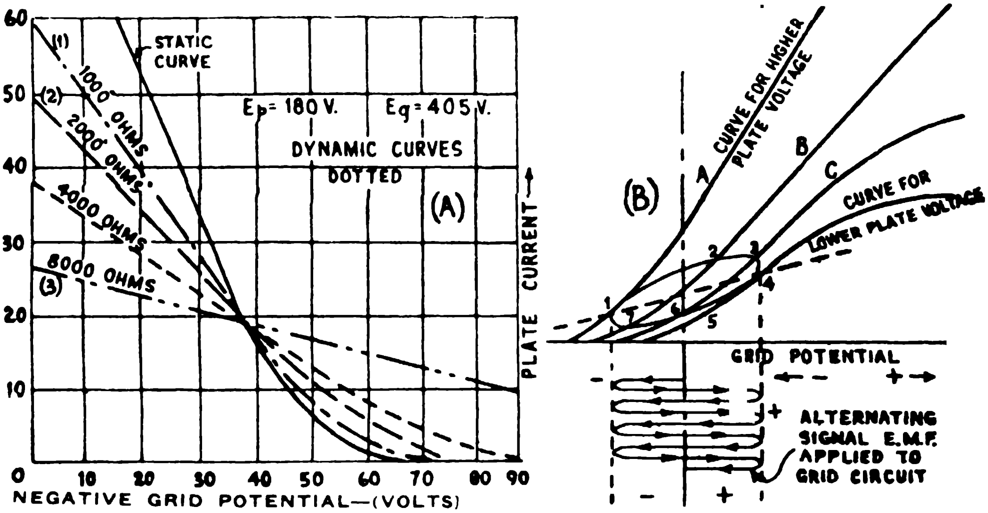


Fig 210—(A) Static and dynamic Eg-Ip characteristic curves for a typical vacuum tube with various values of resistance load connected in the plate circuit.
(B) Dynamic Eg-Ip characteristics for a tube with an impedance load in the plate circuit

value of R_L, a different curve will result for each value of R_L employed, as shown: One curve labeled "static" is the static characteristic curve, all the rest are the dynamic curves. These are published here by courtesy of Radio Broadcast Magazine.

The dynamic characteristic is, as its name implies, a curve indicating how the tube will function under actual operating conditions. The static characteristic curve, although valuable in giving an idea of the general characteristics of a tube, gives no indication at all of the tube's actual performance. Under actual operating conditions, a tube always operates with a certain load in its plate circuit and consequently a curve taken to indicate the tube's performance should be made with some load in the plate circuit. One curve marked "dynamic" was taken when the tube had 4000 ohms resistance in its plate circuit. The difference between the static and the dynamic curves is considerable, as will be seen. The curves were taken with an applied B voltage (E_b) of 180 volts and the grid voltage (E_g) was varied in steps, the plate current being measured at each step.

The other curves are dynamic characteristics taken with different resistances in the plate circuit. Curve No. 1 was made with 1000 ohms resistance, No. 2 with 2000

ohms, and No. 3 with 8000 ohms. It will be noticed that with the higher plate load resistances, the curves have longer straight portions. The curves all cross at about 40 volts because this grid voltage represents the initial d-c potential placed on the grid and the curves are made by increasing and decreasing the grid voltage about this average value. It is necessary in taking the curves to adjust the plate voltage each time so that with the different resistances the same plate current is obtained at 40.5 volts on the grid.

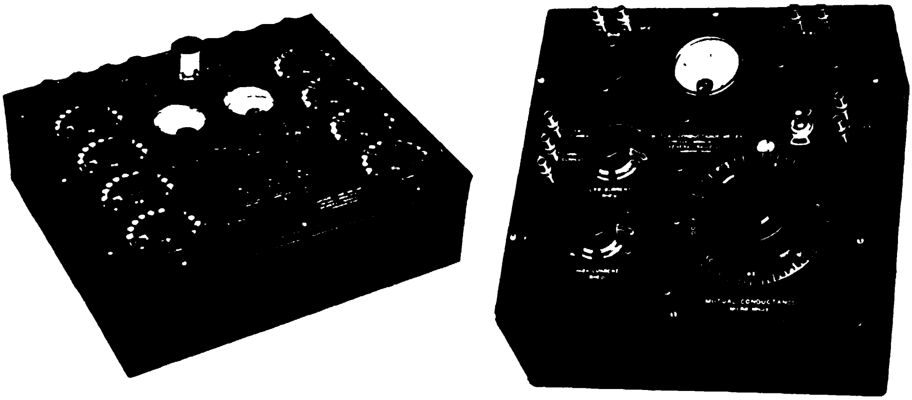
It will be seen that the dynamic curves are much flatter and longer than the static curve. Therefore, the plate current variations for a given grid potential variation, are smaller in magnitude. The mutual conductance of the circuit is no longer as high as the value for the tube alone. The slope of the curve tells us how much plate current will flow through the resistor when a given potential is applied to the grid, under actual circuit conditions, and it is therefore very useful. Of course what we are ultimately interested in are the dynamic characteristics, but if we find that the static characteristics are normal, we can be fairly certain that the tube will operate properly.

294. Tube with impedance plate load: When the plate circuit load is an impedance, that is, contains reactance as well as resistance, the dynamic characteristic curves are somewhat different. A case of this kind would occur if the primary winding of a coupling-transformer, or an impedance coil, were connected in the plate circuit as in the case of transformer or impedance coupled r-f and a-f amplifiers. In this case, on account of the reactance in the plate circuit, the phase difference between the plate and grid potentials may differ from 180 degrees, and the dynamic characteristic of the plate circuit takes the form of a loop as shown at (B) of Fig. 210.

The tube starts working at conditions represented by say, point 1 on a certain characteristic curve A, when the signal voltage is at the lowest value in its negative half cycle, as shown by the wave on the signal e.m.f. curve below. As the signal e.m.f. becomes positive during the next half cycle of the signal e.m.f. curve, the action of the grid of the tube moves over to point 2 on curve B representing a lower effective plate voltage, due to the fact that the effective plate voltage has dropped because of increased drop in voltage in the load impedance. In this way, as the positive half of the cycle of the signal wave goes to maximum, the tube works successively at points 1, 2, 3 and 4. Then as the grid potential becomes more negative due to the signal e.m.f., the action of the tube returns back to point 1, but along a different path 4 - 5 - 6 - 7; since, due to the fact that the entire plate circuit consists of the resistance from plate to cathode in series with the load impedance, the circuit is a reactive one and the plate current changes are not exactly in step with the grid potential changes (see Figs. 109 and 110), whereas if the plate load were pure resistance and the plate current changes were in step with the grid potential changes, the successive operating points would go back along the straight line 4-1. Actually since the plate current reductions and the reduction in the voltage drop in the load impedance lag behind the grid potential changes, the plate current is lower at each instant than it would otherwise be, so the action of the tube returns along points 4 - 5 - 6 - 7 to 1. The curve 1 - 2 - 3 - 4 is above the straight line 1 - 4 for the converse reason, i.e., the variations in voltage drop lag behind the variations in the grid potentials so the plate current at each instant is a little bit higher than it would be if they were in step, so points 1 - 2 - 3 lie above the straight line 1 - 4. As we shall see later, in order to obtain distortionless amplification it is necessary to make the operating characteristics 1 - 2 - 3 - 4 - 5 - 6 - 7 - 1 approach the straight line 1 - 4, since unless this is a straight line, the output plate current variations are not an enlarged reproduction of the input signal voltage variations impressed on the grid circuit. This can be done by making the external load impedance larger than the plate resistance of the tube. Thus the static characteristic curves may be quite different from the dynamic curves.

This does not mean that the static characteristic curves of a vacuum tube are of no value. They are a great help in understanding the dynamic characteristics and they also show many important facts regarding vacuum tubes. They simply must be used with a full understanding that they do not show the exact conditions existing when the tube is in actual operation in practical circuits.

295. Bridge methods of finding dynamic characteristics: The determination of the actual tube constants under the dynamic circuit conditions just described, i.e., with varying grid potentials, is usually accomplished with some form of bridge circuit. An a-c potential from some source such as a 1,000 cycle oscillator or buzzer is usually applied to the



Courtesy General Radio Co.

Fig 211—**Left:** Vacuum tube bridge for laboratory measurement of dynamic or static characteristics of vacuum tubes. See Fig. 212.
Right: Meter for rapid measurement of mutual conductance.

grid circuit of the tube under test. A 1,000 cycle e.m.f. source is usually employed as a signal voltage since the minimum sound in the earphones may be more easily detected on account of the great sensitivity of the ear to sounds of 1,000 cycles. A bridge for measuring the tube constants is not the ordinary type of impedance network. It depends upon the balancing of the amplified signal voltage in the plate circuit by an opposing voltage so that no sound is heard in the earphones connected in the plate circuit (after the manner of the ordinary impedance bridge). A typical laboratory type of vacuum tube bridge designed for rapid measurements is shown at the left of Fig. 211. By means of several switches provided, it is possible to obtain the circuit arrangements shown in Fig. 212, in order to make various measurements. A bridge of this type may be used for easy and rapid measurement of filament characteristics of amplification constant, a-c plate resistance and mutual conductance. Either static or dynamic characteristics may be measured with it. As complete instructions for operating the bridge are furnished by the manufacturer, they are not given here.

· The bridge is designed to combine accuracy with great ease and speed of manipulation. All changes in the bridge to obtain the different circuits used, are made by the use of throw switches. The balancing adjustments are on a dial decade scheme. There is no necessity for removing plugs or changing connections.

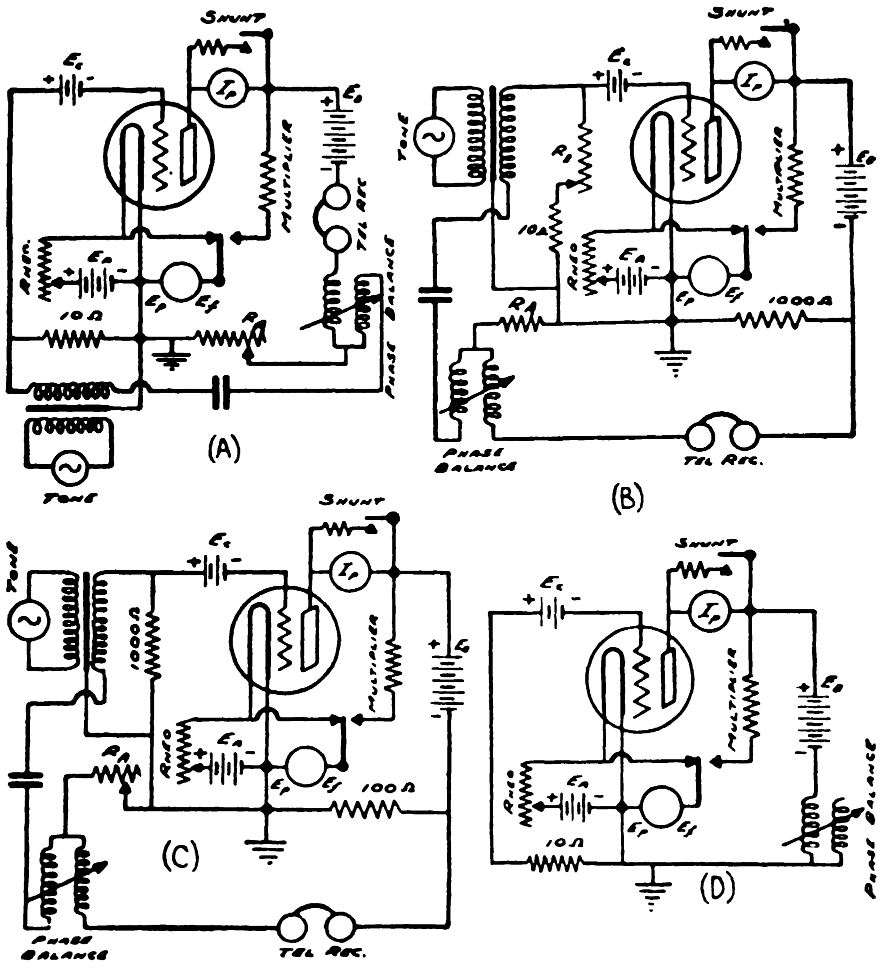


Fig 212.—Circuit arrangements which may be obtained by means of the key switches provided in the vacuum tube bridge of Fig 211
(A) circuit for measuring amplification constant (B) circuit for measuring the a-c plate resistance (C) circuit for measuring mutual conductance (D) circuit for taking the static characteristics

Of the three fundamental dynamic constants of a tube, the mutual conductance gives the most positive indication of the tube behavior, since it involves the ratio of the other two constants. While it is not a complete indication of the comparative merit of tubes of differing types, it is a positive indication among tubes of the same type. If a tube fails to meet the

standard specifications of its type, either through faulty filament emission or an incorrect spacing of the elements, the mutual conductance always will be lowered and it may be detected. Since the mutual conductance is very easily measured, this constant is the one most suited for use as an acceptance standard for purchasers, and for use in factory, store or laboratory for rapid checking of tubes against a standard value. A mutual conductance meter designed to measure this constant rapidly, is shown at the right of Fig. 211. This device should not be confused with the vacuum tube bridge just described, which is a laboratory instrument designed to give accurate measurement of all three constants.

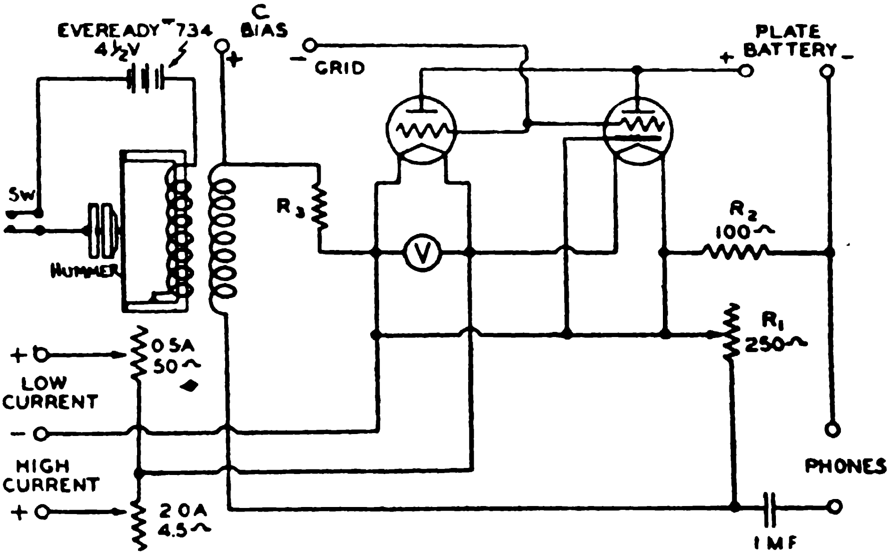


Fig. 213—Circuit diagram of the mutual conductance meter shown at the right of Fig. 211.

A commercial type of mutual conductance meter is shown at the right of Fig. 211. Its circuit diagram is shown in Fig. 213. This is a null-point bridge instrument excited by a 1,000 cycle e.m.f. produced by a self contained microphone hummer and battery. A standard four-prong socket is provided, as well as a 5-prong socket for five-prong separate-heater tubes. All tube batteries are to be connected externally, and any desired plate voltage may be applied to the tube as well as any desired grid biasing voltage. The instrument is equipped with a voltmeter for indicating the voltage across the filament. A low-resistance high-current, and a high-resistance low-current rheostat are provided for filament voltage adjustment of all types of tubes. By the use of one or the other of the rheostats it is possible to adjust the filament voltage to the correct value for any standard tube. A pair of earphones is used to indicate when the bridge is balanced. If the bridge is operated in a noisy environment, an external stage of amplification should be employed to bring up the sound level in the earphones.

Values of mutual conductance having a precision of within 5 per cent are quickly obtained by the manipulation of the single dial to give silence in the phones. This is calibrated to read the mutual conductance in micromhos directly. When testing screen grid tubes, the negative terminal of the C battery is connected directly to the control grid cap on the screen grid tube by means of a wire and a clip. A screen grid battery is connected with its negative terminal to A- and its positive terminal to the

DETECTORS AND AMPLIFIERS

Type	Purpose	Base	Dimensions Max. Overall: Length	Dimensions Max. Overall: Diam.	Cathode Type	Rating: Filament or Heater Volts	Rating: Filament or Heater Amperes	Rating: Filament or Heater Supply	Rating: Plate Max. Volts	Rating: Screen Max. Volts	Plate Supply Volts	Negative Grid Bias Volts: DC Fil.	Negative Grid Bias Volts: AC Fil.	Screen Volts	Plate Current Milliamp.	A.C. Plate Resistance Ohms	Mutual Conductance Micromhos	Voltage Amplification Factor	Ohms Load for Stated Power Output	Power Output Milliwatts
WD-11	Detector & Amplifier	WD 11	[illegible]	[illegible]	—	1.1	0.25	D.C.	135		90 135	4.5 10.5			2.5 3.0	15500 15000	425 440	6.6 6.6	15500 10000	7 [illegible]
WX-12	Detector & Amplifier	UX	[illegible]	[illegible]	—	1.1	0.25	D.C.	135		90 135	4.5 10.5			2.5 3.0	15500 15000	425 440	6.6 6.6	[illegible] 10000	7 35
UX-112-A	Detector & Amplifier	UX	[illegible]	[illegible]	—	5.0	0.25	D.C.	180		90 135	4.5 9.0			[illegible]	[illegible]	1500 1600	8.5 8.5	[illegible]	[illegible]
UV-199	Detector & Amplifier	UV	[illegible]	[illegible]	—	3.3	0.063	D.C.	90		90	4.5			2.5	15500	425	6.6	15500	7
UX 199	Detector & Amplifier	UX	[illegible]	[illegible]	—	3.3	0.06	D.C.	90		90	[illegible]			2.5	15500	425	6.6	15500	7
UX-200-A	Detector	UX	[illegible]	[illegible]	—	5.0	0.25	D.C.	45	—	45	Grid Return to (−) Filament			1.5	30000	666	20	—	—
UX-201-A	Detector & Amplifier	UX	[illegible]	[illegible]	—	5.0	0.25	D.C.	135		90 135	4.5 9.0			2.5 3.0	11000 10000	725 800	8.0 8.0	[illegible] [illegible]	15 55
UX-222	Radio Freq. Amplifier	UX	[illegible]	[illegible]	—	3.3	0.132	D.C.	135	67.5	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	350 480	300 700	—	—
UX 222	Audio Freq. Amplifier	UX	[illegible]	[illegible]	—	3.3	0.132	D.C.	135	67.5	[illegible]	[illegible]		22.5	[illegible]	1000000	[illegible]	[illegible]	—	—
UY-224	Radio Freq. Amplifier	UY	[illegible]	[illegible]	—	2.5	1.75	A.C. or D.C.	[illegible]	90	180 180 [illegible]	[illegible]	[illegible]	[illegible]	4.0 4.0 [illegible]	[illegible]	1050 1000 [illegible]	420 400 [illegible]		—
UY-224	Biased Detector	UY	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	[illegible]	90	[illegible]	Approx. [illegible]		[illegible]	Plate Current to be adjusted to [illegible] ma. with no Input Signal					
UY 224	Radio Freq. Amplifier	UY	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	[illegible]	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]		
UX 226	Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UY 227	Detector & Amplifier	UY	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UY-227	Biased Detector	UY	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	[illegible]		[illegible]	[illegible]			Plate Current to be adjusted to [illegible] ma. with no Input Signal					
RCA-230	Detector & Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]		[illegible]				[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RCA-232	Radio Freq. Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
RCA-232	Biased Detector	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	Plate Current to be adjusted to [illegible] ma. with no Input Signal					
RCA 232	Audio Freq. Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]					
RCA-235	Radio Freq. Amplifier	UY	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	[illegible]	90	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
RCA-236	Radio Freq. Amplifier	UY	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]	[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		
RCA-237	Detector & Amplifier	[illegible]	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]		[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UX 240	Voltage Amplifier	UX	[illegible]	[illegible]		[illegible]	[illegible]	D.C.	180		[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]		

[illegible footnotes: *For Grid Leak Detection ... ; †Applied through plate coupling resistor of [illegible] ohms ...]

POWER AMPLIFIERS

Type	Purpose	Base	Length	Diam.	Cathode Type	Fil. Volts	Fil. Amperes	Fil. Supply	Plate Max. Volts	Screen Max. Volts	Plate Supply Volts	Grid Bias DC	Grid Bias AC	Screen Volts	Plate Current	A.C. Plate Resistance	Mutual Conductance	Ampl. Factor	Ohms Load	Power Output
UX 112 A	Power Amplifier	UX	[illegible]	[illegible]	—	5.0	0.25	A.C. or D.C.	180		[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UX 120	Power Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]		[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UX 171 A	Power Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	180		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UX-210	Power Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RCA-231	Power Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]		[illegible]	[illegible]			[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RCA-233	Power Amplifier	[illegible]	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RCA-238	Power Amplifier	[illegible]	[illegible]	[illegible]	—	[illegible]	[illegible]	D.C.	[illegible]	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UX-245	Power Amplifier	UX	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C. or D.C.	[illegible]		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RCA-247	Power Amplifier	UY	[illegible]	[illegible]	—	[illegible]	[illegible]	A.C.	250	250	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
UX-250	Power Amplifier	UX	[illegible]	[illegible]	—	7.5	1.25	A.C. or D.C.	450		[illegible]	[illegible]	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

*Screen Current [illegible] Milliamperes **Screen Current [illegible] Milliamperes ***Screen Current [illegible] Milliamperes

RECTIFIERS

Type	Purpose	Base	Length	Diam.	Cathode Type	Fil. Volts	Fil. Amperes	Fil. Supply	Ratings	Value	Remarks
UX-280	Full Wave Rectifier	UX	[illegible]	[illegible]	—	5.0	2.0	A.C.	A.C. Voltage per Plate (Volts RMS) D.C. Output Current (Maximum MA.) A.C. Voltage per Plate (Maximum Volts RMS) D.C. Output Current (Maximum MA.) A.C. Voltage per Plate (Maximum Volts RMS) D.C. Output Current (Maximum MA.)	[illegible]	For d.c. output voltage delivered to filter, see typical rectifier curves in Technical Bulletin
UX-281	Half Wave Rectifier	UX	[illegible]	[illegible]	—	7.5	1.25	A.C.	A.C. Plate Voltage (Maximum Volts RMS) D.C. Output Current (Maximum MA.)	[illegible]	For d.c. output voltage delivered to filter, see typical curves in Technical Bulletin

TYPES FOR AMATEUR AND EXPERIMENTAL RADIO USES

Type	Purpose	Base	Dimensions Maximum Overall: Length	Diam.	Cathode Type	Filament Volts	Filament Amps.	Filament Supply	Normal Plate Volts	Voltage Amplification Factor	Negative Grid Bias	Screen Voltage	Plate Current	Plate Dissipation	Power Output
UX-852	Oscillator, R.F. Power Amplifier	UX	[illegible]	[illegible]	—	10.0	3.25	A.C.	2000	12	[illegible]		[illegible]	[illegible]	[illegible]
UX-865	Oscillator, R.F. Power Amplifier	UX	[illegible]	[illegible]	—	7.5	2.0	D.C.	500	150	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
RCA-866	Half Wave Rectifier	UX	[illegible]	[illegible]	—	2.5	5.0		Maximum Peak Inverse Voltage 5000 Volts; Maximum Peak Plate Current 0.6 Ampere; Approximate Tube Voltage Drop 15 Volts						

Courtesy R C A. Radiotron Co

Fig. 214—Table of average characteristics of the various types of vacuum tubes.

C-terminal of the tester, for the screen grid of the tube connects to the normal G terminal of the tube socket.

It is desirable that tubes be tested for short-circuited elements before being placed in the mutual conductance meter. A glance at the schematic diagram will show that when any of the elements in the tubes are shorted, the entire plate battery is impressed across R2, and although R2 will carry 250 milliamperes, it will not withstand the heavy short-circuit current from the plate battery. If it is not practical to make a preliminary test for short-circuited elements, a protective relay or a fuse may be inserted in series with the plate battery.

296. Table of vacuum tube characteristics. As there are many different types of tubes for various special applications, and designed to operate from various sources and values of voltages and currents, it is convenient to have all of their important constants and operating characteristics arranged in a chart or table for convenience. A table of this kind is shown in Fig. 214. This is reproduced here by courtesy of the R.C.A. Radiotron Co., Inc. The student should learn to look up values from this chart and he should spend some time acquainting himself with the different general type numbers of the various tubes as well as the operating filament, grid and plate voltages recommended for them, and the values of mu, mutual conductance, a-c plate resistance, and undistorted power output resulting. A good working knowledge of the data contained in this table will be of great assistance in all work concerning the use of vacuum tubes.

For instance, referring to the 227 tube and reading over to the various columns at the right, we find that this tube may be used either as a detector or an amplifier, has a UY type base, may obtain its filament supply of 1.75 amperes at 2.5 volts either from an a-c or d-c source, will operate as a detector with a plate voltage of 45 volts, etc. We find that when used as an amplifier, with an effective plate voltage of 90 volts, and a C-bias of 6 volts, the plate current is 2.7 milliamperes, the a-c plate resistance is 11,000 ohms. the mutual conductance is 820 micromhos, the mu is 9, the ohms load for maximum undistorted output is 14,000 ohms, and the maximum undistorted output is 30 milliwatts. For other values of plate and C bias voltages, these values are different as shown. In this way, this table can be used to supply a great deal of valuable operating data about all of the types of tubes listed.

REVIEW QUESTIONS

1. What are the three important constants of a vacuum tube?
2. Of what use are vacuum tube characteristic curves?
3. Why does a certain electric potential on the grid have a greater influence over the space charge and plate current flow in a tube than an equal potential applied to the plate?
4. For a given tube the same change in plate current is produced whether the plate voltage is changed by 50 volts or the grid potential is changed by 5 volts. What is the amplification factor of this tube?
5. Draw an E_g - I_p characteristic curve for a tube operating with 90 volts applied to the plate, using the following values of E_g - I_p; —10 volts, .2 m.a.; —8 volts, 0.5 m.a.; +6 volts, 12 m.a. Find the amplification factor, of the tube at some point on this curve, assuming that the E_g - I_p characteristic for a plate voltage of say 80 volts may be drawn parallel to and near this one.

6. Find the mutual conductance of the tube in problem (5), from the curve.
7. Find the d-c plate resistance of the tube in problem (5) at a grid potential of —4 volts. Find the a-c plate resistance.
8. Define (a) amplification constant, (b) mutual conductance, (c) d-c plate resistance, (d) a-c plate resistance of a tube.
9. Why do the mutual conductance and the a-c plate resistance of a tube vary if the plate and grid voltages are varied?
10. Why is the plate current always larger than the grid current? Under what conditions may current flow in the grid circuit of a vacuum tube?
11. The power output of a vacuum tube is greater than the power input. Does this mean that the tube creates power? Explain just where the extra power comes from.
12. One tube has an amplification factor of 200, another type has a value of 5. Does this mean that the first tube is a better tube to use in any type of amplifier than the latter is? Explain in detail.
13. Explain in detail why the signal voltage to be amplified is always impressed across the grid circuit of a vacuum tube rather than into, or across, any of the other circuits.
14. What tube constant do most commercial tube checkers measure? Why?
15. Draw a simple circuit diagram of a tube checker designed to check the mutual conductance of a simple 3-electrode tube. Ex plain its operation.
16. What is the difference between the static and dynamic characteristic curves of vacuum tubes? Why are they different? Which gives more accurate information concerning the characteristics of a vacuum tube under actual operating conditions? Why?
17. If you were interested merely in finding out whether various tubes in a batch were in good operating condition, what test would you apply to them?
18. If you wanted to find out the exact characteristics of the tubes in question 17, how would you test them? Why?
19. A 90 volt B battery is connected in the plate circuit of a vacuum tube in which there is also a 0.1 megohm resistor. The plate current flowing is 0.2 milliampere. What is the effective voltage being applied to the plate of the tube? What voltage appears across the resistor? Draw a sketch with all of the circuit conditions and values marked on it and explain.
20. Would a tube whose E_g - I_p characteristic curve was very steep have a higher or lower amplification constant than one whose curve is not so steep? Why?
21. What is meant by the term "transconductance"?

CHAPTER 19

CONSTRUCTION FEATURES OF VACUUM TUBES

MANY TYPES OF TUBES — ELECTRON EMITTING FILAMENTS — THORIATED TUNGSTEN FILAMENT — REACTIVATING THORIATED TUNGSTEN FILAMENTS — OXIDE COATED FILAMENTS — INDIRECTLY HEATED CATHODES — CATHODES FOR A-C FILAMENT OPERATION — QUICK HEATER TUBES — THREE-ELECTRODE INDIRECT HEATER TUBE — PARALLEL AND SERIES OPERATION OF HEATER FILAMENTS — WHAT SCREEN GRID TUBE DOES — FEEDBACK IN R. F. AMPLIFIER — ELECTRODE ARRANGEMENT IN S. G. TUBE — TYPES OF S. G. TUBES — CHARACTERISTICS OF S. G. TUBES — SPACE-CHARGE GRID TUBE — VARIABLE MU S. G. TUBE — POWER TUBES — HEATING OF THE PLATE; SECONDARY EMISSION AND SPACE CHARGE — POWER PENTODE TUBE — SCREEN GRID PENTODE — POWER SENSITIVITY — GRID BIAS FOR DIRECT HEATER AND INDIRECT HEATER TUBES, AND FOR SEVERAL TUBES — VACUUM TUBE CONSTRUCTION AND MANUFACTURE — EFFECT OF GAS — REVIEW QUESTIONS.

297. Many types of tubes: Vacuum tubes are made in many forms with electrodes of various sizes, shapes and arrangements, each designed to give the tube certain special desired characteristics.

The receiving types vary in filament rating, electron emitting characteristics, mutual conductance, a-c plate resistance and amplification constant. They also vary in detector sensitiveness, power output and overload capacity. Various types of vacuum tubes are shown in Fig. 215. This is only a part of the list of the many types of tubes made. The filaments may be designed to be operated from dry cells, storage batteries or raw alternating current. The tubes can be constructed to handle from one or two milliwatts to several thousand watts of power. The filaments may be either of the thoriated tungsten type or coated with the oxides of barium or calcium to increase the electron emission for a given temperature. In many tubes, the filament does not emit electrons at all, the electron emission being obtained from a separate cathode heated by the filament. Filaments may be made in the form of round wires, or flat ribbons; arranged in the form of a straight wire, an inverted V, a double V, etc.

The plates are usually plain, box shaped, or nearly cylindrical, with the grids corresponding. The relative spacing of grid, filament, and plate, as well as the fineness of the mesh in the grid, also depends on the type of tube. Some tubes have been designed with a multiplicity of filaments, grids and plates. Some types of tubes have even been designed with multiple elements so as to contain within the glass bulb all the necessary parts for one or two amplifier stages. These have attained

some popularity in the United States. While a large number of types of tubes are manufactured, we will now see that they all possess generally similar construction features. We will also see how the special characteristics are obtained.

298. Electron-emitting filaments: As explained in Article 264, all practical vacuum tubes in use at the present time obtain a supply of electrons for their operation by means of some body called the *cathode* which is heated by an electric current flowing through a filament wire. The student is advised to refer again to Fig. 189 for a review of the various methods of obtaining an electron emission. The question is often asked as to whether radium could be used as the electron emitter in vacuum tubes.

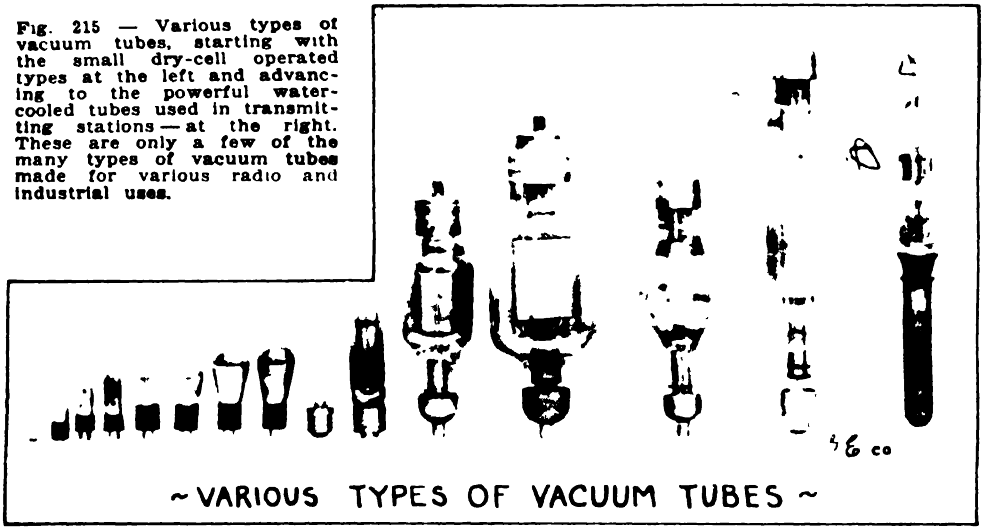


Fig. 215 — Various types of vacuum tubes, starting with the small dry-cell operated types at the left and advancing to the powerful water-cooled tubes used in transmitting stations — at the right. These are only a few of the many types of vacuum tubes made for various radio and industrial uses.

Radium gives out, among other things, a continuous stream of electrons. A filament of metallic radium in a vacuum tube would produce electrons continuously, whether it were hot or cold, for thousands of years. It would avoid, therefore, any necessity for heating the filament. The heating battery could be dispensed with and the filament would never wear out or burn out.

This would be very pleasant, but filaments of metallic radium are impossible if for no other reason than because one of them would cost some half-million dollars. What is actually proposed, and has been many times attempted, is to construct a tube in which the hot filament as a source of electrons is replaced by a preparation containing very little radium but which is still capable of giving off a continuous stream of electrons. A familiar example is the material used on the face figures of the so-called radium watches. This material really does contain a little radium. The activity of the radium produces light from another constituent of the material causing the figures to shine in the dark.

Now similar compositions containing radium can be made so that they will produce electrons instead of light and they can be put into vacuum tubes instead of the filament. A radium tube is, therefore, possible in theory. Whether it would be really useful is another matter, since there would be no practical way of controlling the electron emission in order to produce tubes with desired characteristics easily controlled during manufacture.

We will first consider the filaments used in those tubes in which the electrons are emitted directly from the heated filament itself, i.e., the filament is the *cathode*, as shown at (B) and (C) of Fig. 189. Since the purpose of the filament is to produce heat, it makes no difference so far as the emission of electrons by heating is concerned, whether the filament is heated to red heat by current from dry cells, a storage battery or an electric light line, provided the proper voltage is supplied to it. Any of these sources of voltage supply may be used, but the ordinary electric light line is probably the most widespread and convenient source of filament voltage commonly employed.

Some substances emit electrons readily at rather low temperatures, while most materials give off very few even though heated to extremely high temperatures. It has been found that the oxides of the rare earth metals, thorium, barium, calcium and strontium, give off a more abundant supply at easily obtained temperatures than any other materials of reasonable cost thus far produced, so they are used in vacuum tubes for producing the electron emission. As these materials are not mechanically strong enough to be made into self-supporting filaments and do not conduct electric current very well anyway, a filament of some wire such as tungsten, nickel or platinum, capable of being operated continuously at high temperatures without melting, is employed to carry the current and act as a rigid structure for supporting the electron-emitting material. Two types of cathodes of this form are in general use today, the thoriated tungsten filament and the oxide-coated filament. The use of the latter is rapidly increasing and it is being employed in all of the new types of tubes, but since the thoriated tungsten filament is still being used in the tubes which are listed in the reactivation table of Article 300 as being capable of being reactivated, a short description of it will be given here.

Since the function of the filament in the type of tube now being considered, is to emit electrons, it is evident that it is desirable from the point of view of life of the filament wire, and electrical power consumed in the filament circuit, to use an electron-emitting material which will emit the greatest quantity of electrons at the lowest operating temperature. Pure tungsten wire is not a very good electron emitter, thoriated tungsten wire is better and barium and strontium oxides are still better. For instance, for the same amount of power in watts used in the filament circuit (same normal operating temperature), when the plain tungsten has an emission represented by 1, the thorium's emission is represented by about 20, and the emission of the oxide coated filament is about 120. The advantage of the oxide coated filament is apparent. Under normal operating conditions, thoriated tungsten filaments are operated at a white heat at about 1700 degrees Centigrade in order to secure sufficient emission, whereas oxide-coated filaments give sufficient emission when operated at a dull red heat at about 750 degrees Centigrade, with corresponding longer life. For a given emission current, the thoriated tungsten filament takes one-

fourth the electrical heating power required by a pure tungsten filament. An oxide-coated filament requires less than one-half that required by a thoriated filament.

299. Thoriated tungsten filament: At the present time, some commercial types of tubes still use the thoriated tungsten filament. These are the ones listed as being capable of reactivation in the table in Article 300.

The thoriated tungsten filament is really a tungsten filament having thorium distributed throughout its mass, and a very thin layer of the metal thorium on its surface. The tungsten serves merely to heat the thorium and to renew the thorium layer as it is used up, the electron emission coming wholly from the thorium layer. The raw filament wire is made of tungsten impregnated with from one-half to one per cent of thorium oxide and some carbon. (Tungsten is the metal also used for the filaments of incandescent lamp bulbs because of its ability to withstand high temperature without melting.)

When such a filament is heated, two important actions take place. As the temperature is increased to about 2,500 degrees Centigrade, some of the thorium oxide is reduced to metallic thorium, and then this gradually works its way to the surface of the filament. At this temperature, the thorium which diffuses to the surface of the filament vaporizes immediately, leaving only pure tungsten at the surface. If the temperature is then lowered to about 1,800 degrees Centigrade for a few minutes, the thorium wanders or diffuses through the filament and when it reaches the surface (provided the vacuum is about perfect) remains there and gradually forms a layer of metallic thorium atoms which never exceeds a single atom in depth. It is this almost inconceivably thin layer which increases the emission over a hundred thousand times. When more thorium atoms work their way to the surface and come up under other thorium atoms already there, the latter at once evaporate, thus maintaining the layer only one atom thick. If the temperature is raised a few hundred degrees, the metallic thorium is formed from the oxide more rapidly and comes to the surface more abundantly, but it does not stay on the surface. It evaporates at once, leaving a tungsten surface.

This film is very sensitive and must not be heated to too high a temperature, or it will evaporate. It is necessary to operate such a filament within a narrow range of temperature close to 1,700 degrees Centigrade, where the ratio of evaporation is small and the temperature is high enough for the thorium to diffuse gradually to the surface and continually replenish the layer as it is used up by the normal operation of the tube. In the UX-201 A tube which uses this type of filament for instance, this condition obtains approximately when five volts is applied to the filament, sending a current of 0.25 amperes through it.

The electron emission of tubes employing this type of filament depends upon the presence of a thin layer of thorium atoms on the outer surface of the filament. During the normal operation of the tubes, the thorium on the outer surface gradually evaporates. This is constantly replenished by diffusion of the thorium from the inside of the filament. As long as the filament voltage is normal and is not raised over ten per cent above the rated value, the evaporation and replenishing continues at an equilibrium rate, so that a constant layer of thorium is maintained on the surface.

If too high a filament voltage is used, the rate of evaporation of thorium is increased more rapidly than the rate of diffusion of the thorium to the surface, the thorium surface layer is partially or totally destroyed, and the emission drops to that of pure tungsten (which is practically zero at these temperatures) and the tube operation is impaired. If the tubes are operated at very low voltages, the filament temperature is so low that the process of boiling out the thorium from the interior of the filament becomes abnormally retarded, and the layer is slowly used up.

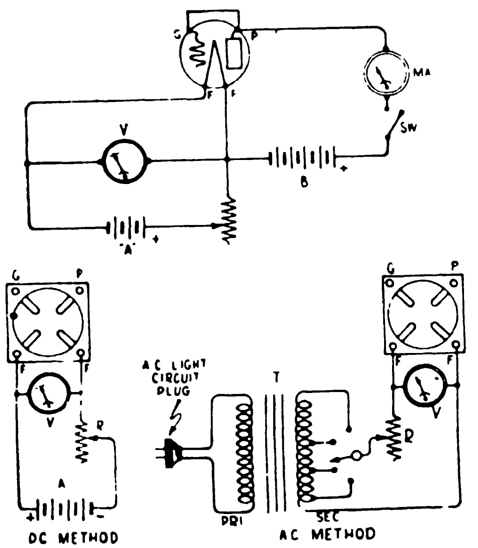
The great majority of thoriated tubes die a natural death, in that their life continues until all of the thorium in the filament is used up. Obviously nothing further can be done with them. Tubes which decrease in operating efficiency after having suffered some of the abuses mentioned above can usually have their thorium layer and full efficiency restored by the simple process of "reactivation" or "rejuvenation". Reactivation consists of cleaning the surface and reducing some of the thorium oxide in the wire to metallic thorium by heating the filament of the tube (with plate and grid circuit disconnected) to a higher temperature than normal, for a short time, by the application of specified high voltages. This is known as "flashing". Then it is operated for a

longer time at a lower temperature. This boils out additional thorium atoms from the interior of the filament and a new active layer is formed on the surface. This is known as "ageing". The plate and grid circuits are left disconnected to prevent them from attracting the thorium electrons to themselves during the process.

300. Reactivating thoriated tungsten filaments: The process of reactivation of thoriated tungsten filaments may be carried out as follows:

All tubes not listed in the table of Fig. 216 as being capable of reactivation have oxide-coated filaments.

Before reactivating a suspected tube, the condition of its filament should be tested by testing its electron emission to see if it is actually below normal. This is done by connecting the grid and plate together as shown at the upper left hand diagram of Fig. 216 and connecting them to the plus terminal of a "B" battery through a milliammeter of suitable range (see table in Fig. 216). The remaining connections are shown. The voltage across the filament, read on V, should first be adjusted to the values specified in the table, for the particular type tube being tested. This also gives the proper "B" voltage to use. Close the switch *just long enough to obtain a reading of the*



TYPE OF TUBE	EMISSION TEST			REACTIVATION PROCESS			
	FIL. VOLTS	PLATE VOLTS	MINIMUM EMISSION ALLOWABLE	FLASHING FIL VOLTS	FLASHING TIME	AGEING FIL VOLTS	AGEING TIME
WD-11 WX-12 C-11 CX-12	1.1	50	6 MA	CANNOT BE REACTIVATED			
UX-199 CX-299	3.3	50	6 MA	12	10-15 SEC	4	30 MIN.
UX-120 CX-220	3.3	50	15 MA	12	10-15 SEC	4	30 MIN.
UX-201A CX-301A	5.0	50	20 MA	16	10-15 SEC	7	30 MIN
UX-200A CX-300A	5.0	50	14 MA	16	10-15 SEC	7	30 MIN
UX-240 CX-340	5.0	50	14 MA	16	10-15 SEC	7	30 MIN.
UX-112A CX-112A	EMISSION READING CANNOT BE TAKEN			CANNOT BE REACTIVATED			
UX-171A CX-371A	5.0	50	50 MA				
UX-210 CX-310	6.0	100	85 MA	NO FLASHING		9	30 MIN
UX-226 CX-326	1.5	50	35 MA	CANNOT BE REACTIVATED			
UX-227 CX-327	2.5	50	35 MA				
UX-216B CX-316B	6.0	125	85 MA	NO FLASHING		9	30 MIN.
UX-280 CX-380	5.0	80	100 MA	CANNOT BE REACTIVATED			
UX-281 CX-381	7.5	150	200 MA				
UX-250 CX-350	7.5	250	560 MA				

Fig 216—Upper left: Circuit for testing emission
Lower Left: Circuits for reactivation.
Right: Voltages and other data for reactivation

emission current on MA. If the reading is *less* than that specified in the table, the tube can usually be improved by reactivation. If the emission is above the minimum specified, the tube is in good condition, and does not need reactivation.

Reactivation may be done in either of two ways, depending on the condition of the tube. For a tube which is operating fairly satisfactorily, but which is to be pepped up to maximum, it is only necessary to disconnect all "B" batteries (or the "B" power unit) from the set and keep the tubes lit up at *normal voltage* for two or three hours, using the rheostats on the set to regulate the brilliancy. The storage "A" battery usually used with the set can be employed to supply the filament current. It is very important that the filament voltage be kept exactly at its proper value, as shown by a good voltmeter.

For the bad cases where the tube gives little or no emission, the more elaborate method must be employed. This consists of two steps: first, operating the filament for a very short time at a specified high voltage (called "flashing"), then operating it at specified lower voltages for a longer period (called "ageing or cooking"), all of this with grid and plate disconnected. During this process the tube is operated without plate voltage, since under normal conditions with the plate voltage on, the electrons would be attracted to the plate as soon as they are brought to the surface of the filament; but by leaving the plate circuit open, they are allowed to accumulate on the

filament and are therefore available in the required quantities when operation is resumed.

Reactivation may be carried on either with direct or alternating current. At the lower left of Fig. 216 are shown the connections for the direct current method. A is a battery capable of furnishing at least 15 volts. R is a rheostat, GPFF is an ordinary tube socket, and V is a good voltmeter. The resistance R is adjusted until the filament voltage is as shown in the "flashing voltage" column in the table, depending on the particular type of tube. This voltage is applied for the length of time specified. Then it is decreased to the value specified as "ageing", for the time shown. It is absolutely necessary that these voltages and times be strictly adhered to, since they are the values which have been found to give best results, after a long series of investigations.

The alternating current from the lighting socket can also be used for reactivation. For the alternating current method it is necessary to use a step-down transformer T, to step down the 110 volts to that necessary for the test. Any transformer giving the desired voltage can be used. This can be one of the small type used for operating door bells or electric toys. The voltage tap nearest the voltage specified should be selected and a rheostat in series with the filament used to adjust the exact voltage as read by the a-c voltmeter. The table gives the necessary data for those tubes which can be rejuvenated. The connections are shown at the lower center of Fig. 216.

A tube can, on the average, be reactivated about six or eight times without any apparent injury to the filament. The emission of various oxide-coated tubes can be tested by the process given, but obviously they *cannot* be reactivated, as will be seen presently from a study of this type of filament

If the tube will not return to normal after proper reactivation treatment, it is proof that the tube has either served its normal life and the supply of thorium in the filament has been used up; or it has been so heavily overloaded that the thorium content has been exhausted or the vacuum impaired. Obviously nothing can be done with such a tube.

301. Oxide coated filaments: Very early work on vacuum tube filaments showed the value of coating the filament with certain oxides to greatly increase the electron emission at low operating temperatures. Tubes used in telephone work have employed oxide-coated filaments of platinum for many years. All of the latest tubes designed for radio receiving, employ either an oxide-coated metal filament or an oxide-coated cathode with a separate-heater filament operating at a dull red heat. The former construction is used in battery-operated tubes and power tubes. The latter type will be described later.

The *oxide-coated* filament is usually made with a very thin ribbon of metal which serves to conduct the current and heat the electron-emitting oxide. Often the ribbon is twisted on itself in such a way as to expose everywhere a sharply curved surface to make the oxide coating stick better. The reader should examine the filaments in some of the larger tubes such as the 245, 280 and 281 types. Several metals have been used for the filament wire or core. All early forms of oxide-coated filaments used a platinum or platinum-iridium filament core. The use of the large quantities of this valuable metal required for the millions of vacuum tubes manufactured, threatened to exhaust all available sources of supply and led to the search for cheaper substitutes. As a result, an alloy called Konel, several alloys of platinum, pure nickel, and alloys of nickel such as silico nickel, titanium nickel, chromium nickel, etc., are being used for filament wire by various tube manufacturers. Pure nickel, heretofore used extensively for filaments, is rapidly being abandoned in favor of these other metals on account of its chemical interaction with the carbonates used for the preliminary coating. The wire used must offer the necessary high electrical resistance, so as to be economical in operation. The best wires are those with a cold resistance several times that of nickel, and with the resistance rising rapidly as they warm up, so as to provide some measure of automatic current regulation. The wire must not stretch unduly when heated, to sag and "short" with the near-by grid. A high melting point is necessary, for the carbonates require about 750 deg. C to provide the necessary emission.

A mixture of barium and strontium carbonates and a binder of nitrates, ordinary water glass, or alcoholic suspensions of barium and strontium oxides, is applied to the filament wire either by successive dippings and bakings in a continuous operation, or by spraying by means of an air brush as in the case of the independently heated cathodes, the applications being repeated until the desired amount of coating material has been deposited. The mixture is baked on to the filament wire in special ovens. When the filament is assembled with the other elements in the glass bulbs, and the bulb is being exhausted, it is lit up to red heat by a source of current. This high temperature breaks down the carbonate coating and the reaction with the air in the tube forms an oxide coating and carbon dioxide gas, the latter being drawn off by the vacuum pump. The coating left on the filament wire core is a combination of barium and strontium oxides which adhere to the filament wire due to friction at the interface together with a certain rigidity of the mass as a whole that results from the interlocking particles. This coating when heated to a dull red heat of about 750° C. by the heat produced in the filament wire due to the current flowing through it, will emit electrons freely. The same electron emission may be obtained from oxide coated platinum at 950° C. Considerable research work is being carried on to determine the exact nature of the effect of the core metal on the emission and whether the real source of electron emission is a layer of metallic barium on the surface of the *core* or whether it takes place from a film of barium of atomic thickness on the surface of the *coating*. It is expected that the results of this work will lead to the development of even more efficient coated filaments than we now have.

Of course, oxide-coated filaments cannot be reactivated as thoriated tungsten filaments can, since all of the active material is on the surface of the filament wire or cathode, and when this is once used up, it cannot be replaced. When the active coating is all used up, the electron emission of the tube drops to a point where it is insufficient to keep the tube operating satisfactorily.

This loss of electron emission may cause impaired set performance in a number of ways. For example, in the case of rectifier tubes the loss of emission means that the rectified voltage supplied by the tube is reduced to a point which reduces the sensitivity of the set, introduces distortion in the output, and limits the volume at which the set can be operated.

In the case of output tubes, the maximum obtainable volume is reduced. If this reduction in volume is carried to an extreme, the set develops an extremely harsh and rasping quality.

In the case of the detector and audio stages, somewhat similar effect in quality is obtained as the tubes wear out.

In the radio frequency stages, a loss of sensitivity and corresponding loss of volume results. The supply of electrons from the cathode should be adequate to supply at least twice the normal plate current, otherwise the tube will be overloaded on strong signals and the quality of the set response is impaired.

The normal operating filament temperature of the usual oxide-coated filament is 750 degrees Centigrade, and this is greatly exceeded when the voltage overload surpasses the 5 per cent limit or allowance specified by the tube manufacturer. The main advantages of the oxide-coated filament or cathode over the thoriated filament, is the lower operating temperature (about 950 degrees Centigrade lower) with consequent increase in filament life and reduced filament power consumption and higher saturation currents. Improved oxide-coated filaments have made possible the construction of tubes designed to obtain their filament current economically from 2-volt batteries of the dry-cell or air-cell type. These filaments are thinner than a human hair and consume .06 ampere at 2 volts. This is a filament power consumption of only .12 watts per tube. Compare this with the old 201 type of tube used several years ago. This required 1 ampere at 5

volts, (5 watts) or 40 times as much power to heat its tungsten filament sufficiently to give off a rather limited supply of electrons.

302. Indirectly heated cathodes: In some cases a more mechanically rugged filament unit consuming a small supply of heating power is required, than is found in the ordinary direct-heated cathode types of filaments just described. Examples of this are in the use of radio receivers on automobiles and airplanes where the tubes are subjected to considerable vibration unless elaborate and costly shock-absorbing mounting schemes are resorted to. The tubes in these receivers must usually obtain their filament current from a battery and economical operation is essential. Also, in those radio receivers in which the filaments are heated by low voltage alternating current supplied by the 110 volt a-c electric light line by a suitable step-down *filament heating* transformer as shown at (D) of Fig. 189, the use of the ordinary type of electron emitter consisting of a coated filament has not proved satisfactory, due to the fact that the varying current causes the filament temperature, the associated fields, the electron emission and plate current to vary, resulting in an annoying hum heard in the loud speaker. For vacuum tube applications of this general class, the indirectly-heated cathode has been developed and is used in many types of standard tubes. The construction of the heater element, insulating bushing and oxide-coated metal cathode thimble proper, were described in Article 264 (which should now be reviewed carefully) and shown in elementary form at (D) of Fig. 189. In this construction the filament simply serves the purpose of producing heat. The electron emission is due to the barium and strontium oxide coating on the cathode surface. General purpose tubes such as the 227, 224, 235, etc., having this type of electron emitter have filaments rated at 2.5 volts and either 1.5 or 1.75 amperes. Special types of tubes such as the 236, 237 and 238 types, designed especially for d-c use in automobile and airplane receivers, or in sets operated directly from the direct current house supply lines, have filaments rated at 6.3 volts and 0.3 amperes. The 2.5-volt heater-type tubes can be operated with either a-c or d-c filament current of the proper voltage. Some 6.3 volt tubes are designed to be operated only with d-c filament current.

303. Cathodes for a.c. filament operation: Instead of employing batteries for supplying the filament heater current for vacuum tubes, it is much more convenient where possible, to use the ordinary 110 volt house electric light supply line as a source of current. If the current available is a-c, it can be stepped down to the proper voltage for the operation of the tube filaments by means of a suitable step-down transformer. However, if alternating current is used to heat the filaments of ordinary "direct-heater" type tubes such as the 201-A type, several very objectional actions occur.

Alternating current starts from zero, rises to a positive value and drops to zero again then reverses its direction and repeats the process over and over 60 times every second (for a 60 cycle e. m. f.) as shown at (A) of Fig. 111 and (A) of Fig. 217. Twice during each cycle the current is actually zero and at other instants it has var-

ious values between zero and its peak value. Since the heat produced at each instant by the flow of current through the resistance of the filament wire is proportional to the square of the current flowing at that instant multiplied by the resistance of the wire ($W = I^2 R$), it is evident that the heat set up in the wire will also increase and decrease 120 times a second. Since the filament in this type of tube is finer than a human hair and therefore does not contain much metal, it cannot hold much heat, and twice every cycle when the current drops to zero, the temperature of the filament and its electron emitting substance also drops as shown at (B) of Fig. 217. This variation in temperature results in a corresponding variation in electrons emitted and in the electron and current flow between the plate and the filament. These variations in the plate current 120 times a second, cause the earphone or loudspeaker diaphragm to vibrate 120 times a second, resulting in a 120-cycle sound wave which sounds as a very objectionable low-pitched hum.

Experiment: Connect up the proper A, B and C batteries and loud speaker to an ordinary radio receiver designed for battery operation with 201-A type tubes and tune in a station. Now disconnect the A battery and connect the terminals of the 5 volt secondary winding of a filament transformer to the A+ and A— terminals of the set. Connect the primary to the 110 volt a-c line, and turn on the a-c current and the set. A loud low-pitched hum will be heard, which drowns out the program being received due to the fact that it modulates the incoming signals at 120 cycles due to the 120 cycle variation in electron emission caused by the unsteady heating of the electron emitters.

Another cause of hum in tubes of this type may be understood by assuming that we have a tube requiring 6 volts for its filament and 45 volts potential on its plate, as shown at (C) of Fig. 217. (The grid can be omitted from this discussion for the present.) The electrons given off by the heated filament are negative charges and since the plate is positive, the electrons will be attracted over from the filament to the plate. But the attracting power of the plate depends upon how positive it is with respect to the filament.

On the diagram we note that 45 volts is the difference in potential existing between the end of the filament "F" and the plate. This is true because the resistance of the heavy wires is negligible. The difference in potential between "D" and the plate, however, cannot be 45 volts, on account of the 6 volt "A" battery. Point "D" is 6 volts positive with respect to point F on the filament and hence the potential difference be-

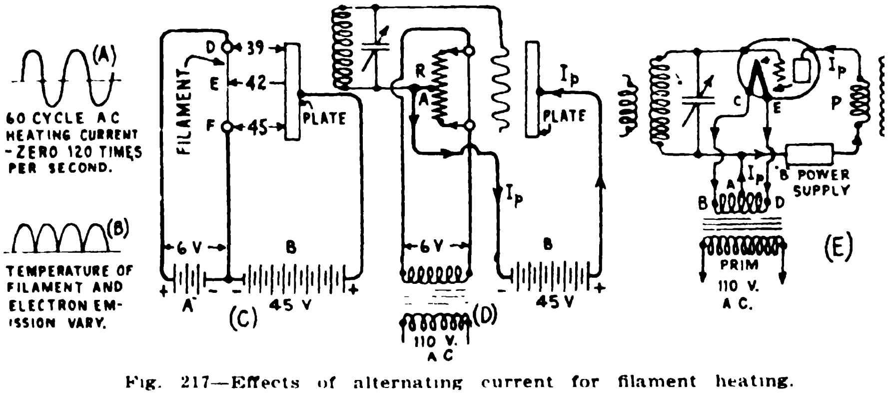


Fig. 217—Effects of alternating current for filament heating.

tween D and the plate is only 39 volts. Between the center point "E" and the plate, the difference is only 42 volts. If the filament is heated by steady direct current, this condition is not objectionable, but if alternating current is used, the voltage of the filament is continually changing; during one half cycle one end is positive with respect to the other, and during the next half cycle it is negative. Since the attractive force of the plate for emitted electrons depends on how positive it is with respect to the part of the filament the electrons came from, it is evident that more electrons will be drawn from the end D of the filament than the end F during one half cycle and more will be drawn from end F than from D during the next half cycle, etc. In the interval between these times, slightly different quantities of electrons are attracted, etc.

The same action takes place in the grid circuit if it is returned to either end of the filament. The fact that the potential of each end of the filament is alternately increasing 3 volts above and then decreasing 3 volts below, that of the center point (for the 6 volt type filament considered for convenience), makes the grid potential vary likewise. If the plate and grid circuits are returned to either end of the filament carrying 60 cycle a-c, then the effect is the same as though a 120 cycle signal voltage were applied in the grid circuit—producing a 120 cycle variation in plate current and resulting in a 120-cycle sound from the speaker (a low-pitched hum).

To reduce this hum in tubes of this type which are to be heated by a-c, a low voltage 1.5 v. filament is used in place of the ordinary 5 volt filament, so that the potential of the ends of the filament only alternates plus and minus .75 volt above that of the center of the filament, and the grid and plate return circuits are returned to a point which is *electrically* midway between the terminals of the filament, that is, a point whose potential is always at the same value as that of the center point of the filament wire, which value does not change. This condition may be likened to that in a see-saw pivoted at the center. The ends of the see-saw alternately move up and down but the center point remains always on the same level.

The electrical center of the filament circuit may be obtained either by means of a center-tapped resistor connected directly across the filament terminals as at (*D*) or by constructing the filament-heating winding with a tap at its electrical center as at (*E*). The former method is preferable, since the resistor can be connected directly at the filament terminals thus insuring a correct center The contact A may be even made adjustable by using a potentiometer for the purpose in order to obtain the exact and best operating point for minimum hum in the loud speaker. The method of using a center tap on the transformer winding has one serious objection in that the heating transformer is usually some distance away from the tube and therefore connecting wires BC and DE may be quite long and may not be of exactly the same length and resistance. In this case even though the center tap of the transformer winding is located accurately, it would not represent the accurate electrical center of the filament circuit of the tube since the resistance from the filament *center* to the winding center tap on side CBA is different from that on the other side EDA.

The path of the plate current I_p is from the positive terminal of the "B" voltage supply, through the plate load, across from the plate to the filament of the tube and then back through the filament-heating winding and out of the center-tap A, back to the negative terminal of the "B" voltage supply as shown by the arrows in (E). If a center-tapped resistor is used, as at (D), the plate current flows from the filament, through the resistor and out of the center tap A, to B minus, as shown by the arrows in (D). In most of the diagrams in this book, the use of the center-tapped resistor will be shown, but the student should remember that the center-tapped filament transformer winding may also be employed provided proper care is taken to keep the connecting wires short and equal in length. Most manufacturers now employ the center-tapped resistor arrangement on account of its advantages of simplicity and cheapness, but there are thousands of old radio receivers in use which have the tapped transformer winding. It should also be remembered that the center-tapped resistor should be located near and *connected directly* to the filament terminals of the tube socket, for if it is placed some distance from it and connected by long wires, the same unbalancing due to unsymmetrical wiring and resulting unequal resistances in the two sides of the circuit may result, and the same objectionable hum as in the case just explained for the transformer winding will be present.

The *total* resistance of the center-tapped resistor used, should be high enough so it does not draw too much current from the filament-supply source. Resistor values used for this purpose have become fairly well standardized; the various values used across filaments of various voltage ratings being approximately as follows. These values are not critical of course:

Filament Voltage	Total resistance of Center-Tapped Resistor—Ohms.
1.5	10
2.5	20
5.0	50
6.3	50 or 75
7.5	75 or 100

Two typical types of center-tapped resistors for this purpose are shown in Fig. 218. The illustration at the left shows the resistance wire wound on the form, with the center-tap connection visible. In the unit at the right, the resistor element is encased in Bakelite to keep out all moisture, etc., and to prevent mechanical damage to the thin resistance wire. Three metal terminals are brought out for connecting it.

There is also a magnetic field surrounding the filament when there is current flowing. If direct current is employed, this field is fixed and although it deflects some of the electrons leaving the filament and forces them to travel much longer paths than others, it has practically no noticeable effect on the operation of the tube.

However, in the case of a-c this magnetic field will be periodically reversed and if the field changes, the paths of the electrons will be changed with the frequency of the a-c. This will result in fluctuations in the plate current, resulting in "hum."

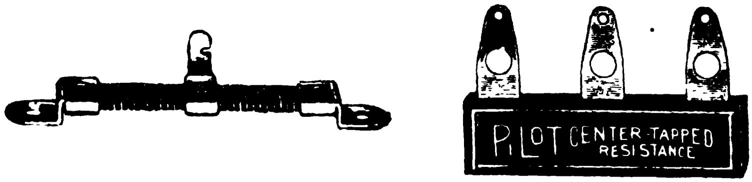


Fig 218—**Left**: Center-tapped resistor showing resistance wire wound on supporting frame **Right**: Center-tapped resistor enclosed in moisture-proof Bakelite

In the 226 type a-c tube, the oxide-coated filament was made very heavy and short and designed to operate with a low voltage of 1.5 volts—across it at a current of 1.05 amperes. It was made round in order to have the greatest thermal inertia for a given mass of filament material. The fact that it was thick enabled it to store a comparatively large quantity of heat during each half cycle, so its temperature did not drop so much during the intervals of zero current, that is, it had a high thermal inertia. Thus a steadier electron emission and plate current resulted. It was possible to obtain a good balance between the electromagnetic and electrostatic fields at the value of plate current desired, by returning the grid and plate circuits to the electrical center of the filament circuit by means of a center-tapped resistor connected across it as at (D) or by a center-tap on the filament winding of the supply transformer. The former method is preferable. Even though its thermal inertia is high and it has rather low hum output, it has been supplanted entirely by the independently heated equi-potential cathode used in the 227, 224, 235, etc., types of tubes. The 226 tube could not be used as a detector due to the hum it would produce.

In the equi-potential cathode construction, already described previously and shown in simple form (without the grid) at (D) of Fig. 189, the heater circuit is entirely independent of the plate and grid circuits. The cathode which emits the electrons is at a constant electrical potential and the direction of the plate current flow is from plate to cathode and back to B minus as shown. The cathode is heated, receiving its heat by conduction and radiation from the filament proper. The thermal inertia of the metal of the cathode, and the insulating bushing (see (D) of Fig. 189) is so great that fluctuations in the a-c current and heat of the filament do not af-

fect the electron emission and plate current. This type of construction is suitable for both detector and amplifier tubes. In the usual type of separate-heater tube there are five prongs, the additional one attached to the cathode being known as the "Cathode" prong. Direct-heater tubes of the 226 type are no longer used in a-c electric radio receivers of recent design.

If the current for the filaments of vacuum tubes in a receiver is to be obtained from a 110 volt d-c electric light line, it is also advisable to use separate-heater type tubes because the d-c current obtained from commercial d-c generators is not absolutely smooth but contains slight ripples due to the rectification by the commutator as shown at (B) and (C)

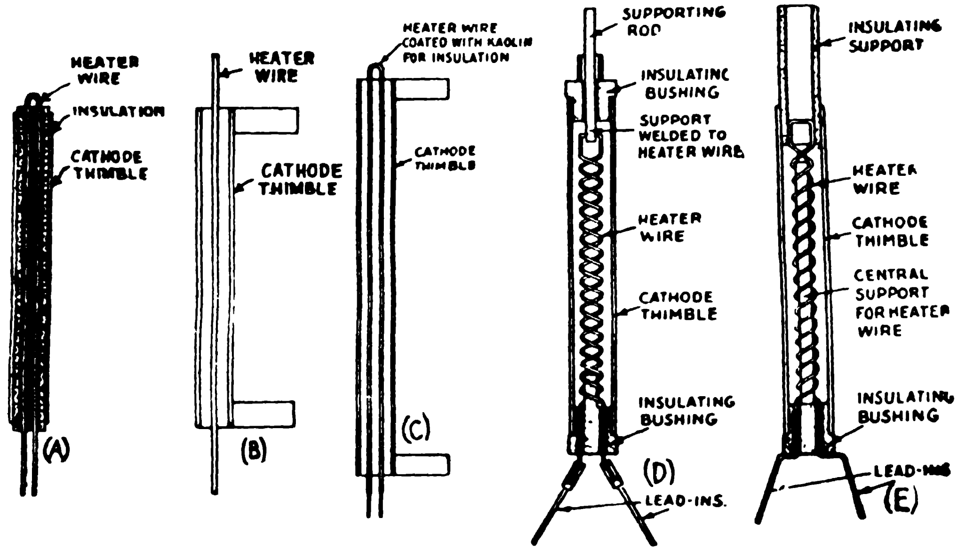


Fig 219—Various types of filament and cathode arrangements in indirectly heated cathode type tubes

of Fig. 68, which will cause hum due to varying filament-heating and electron emission when tubes with ordinary thin filaments are employed.

304. Quick-heater tubes: Filament and cathode arrangements in indirect-heater tubes have undergone a series of changes in order to achieve quick-heating of the cathode when the filament current is turned on. Quick heating has been achieved in various ways, either by a marked reduction in the mass of insulating material between the filament and cathode, by the use of new synthetic ceramic insulators having very good heat conductivity, or by the total elimination of the insulating material, merely relying on the mechanical separation between filament and cathode to prevent electrical contact and possible short-circuiting.

An early type of indirectly-heated cathode is shown at (A) of Fig. 219. The cathode itself is a hollow, oxide-coated nickel thimble or cylinder. The filament is in the form of a hairpin loop of wire usually threaded through a bushing of ceramic material somewhat like porcelain, within the cathode thimble. This insulates the cathode from the

filament, and the two heater wires are placed close to one another so that the alternating current fields set up around the two wires will largely neutralize one another because the currents in the two wires are of opposite phase, with the result that the external field around the heater will be very weak and the resulting hum therefore low. The great disadvantage of this cathode is the time required for the tube to begin functioning. Under the operating conditions obtaining in the average radio receiver, it generally takes from 15 to 30 seconds for the set to begin playing after being turned on.

In an endeavor to reduce this heating time, some tube manufacturers developed the cathode shown at (B). This type of structure resulted in a quick heating cathode but it introduced many serious disadvantages. In the first place, the a-c heater is of the "straight through" type in which the field of the a-c heater current is not made to neutralize itself, with the result that this type of cathode produces entirely too much hum for use in the modern highly sensitive broadcast receiver. It will be evident also that the heater wire must be centered within the cathode thimble by the factory worker; an operation that cannot be accomplished satisfactorily in quantity production. In the second place, the heater wire is supported by long wires in glass beads which are not integral with the cathode. Since the heater wire is not covered with an insulator, the rough handling which a tube gets in shipment and the constant vibration which it receives in use often produces short-circuits of the heater to the cathode, with resulting greatly increased hum and unsatisfactory operation of the tube.

(C) shows a type of cathode construction which was developed in an endeavor to eliminate the serious limitations of the previous cathode. As will be noted, an insulated hairpin is always centered within the cathode thimble. The kaolin insulation employed is a very hard and brittle substance, however, with the result that the repeated heating and cooling of the a-c heater, as the set is turned on and off in use, tends to crack off the insulation from the heater, thereby affording an opportunity for the heater to short circuit against the cathode thimble. It also will be noted that the hairpin heater is hand spaced and supported within the cathode as in the previous construction, and hence is subject to the same trouble. (D) shows a quick-heater, low-hum cathode used in modern high sensitivity receivers. It employs a heater of tungsten wire, coiled into a tight double spiral, which makes it act like a spring. This springy heater is mounted under tension between two insulating plugs in the ends of the cathode. When the wire expands in heating, the springiness of the coiled construction takes up the slack, keeping the heater tight and in the exact center of the cathode. When jolted and jarred, the coil can deflect sideways without breaking, but instantly snaps back into position. The bottom insulating bushing is provided with a short projection which extends up into the heater coil for about two turns. This keeps the end turns from being short-circuited against each other as the operator threads the lead-in wires through the two holes in the bushing and thus assures a good rugged construction at this point.

An improved type of cathode construction is shown at (E). The projection on the bottom insulating bushing has been lengthened to extend the full length of the heater coil. This stiff, hard rod, running the full length of the coil makes it difficult to pull or twist it out of shape when assembling and no strain need be put on the coil to keep it stretched when it heats up.

305. Three-electrode indirect-heater tube: The construction of a general purpose three-electrode 227 type tube with independent heater construction is shown at Fig. 220. Starting at the left, the various parts are shown in the order of their assembly, working up to the completed tube at the right. The grid is in the form of a round spiral wire of molybdenum, wound with spaced turns to allow the electrons to pass through the openings. This fits around the cathode assembly. Around this is the metal plate, usually of nickel. The parts are mounted on a glass stem and sealed in a glass bulb from which all of the air is later exhausted. The plates of many tubes of this type are made of a close-mesh wire screen or a perforated sheet instead of a solid sheet of metal, in order to reduce secondary emission and provide greater heat radiation. This will be considered later.

The arrangement of the elements and terminal markings in a tube of this type are shown in the cut-away view at (A) of Fig. 221, and the common symbol for the tube is shown at (B). The arrangement of the terminals in the five-prong socket required for this type of tube is shown at (C). Notice that the two filament terminals are arranged together, at the left is the cathode and at the right is the plate terminal. The grid terminal is at the rear and separated from all the rest in order to reduce the capacitance between it and the other prongs and contact pieces. This view is drawn looking down on top of the socket. An illustration of a socket of this kind is also shown at the left of Fig. 222. This tube can.be

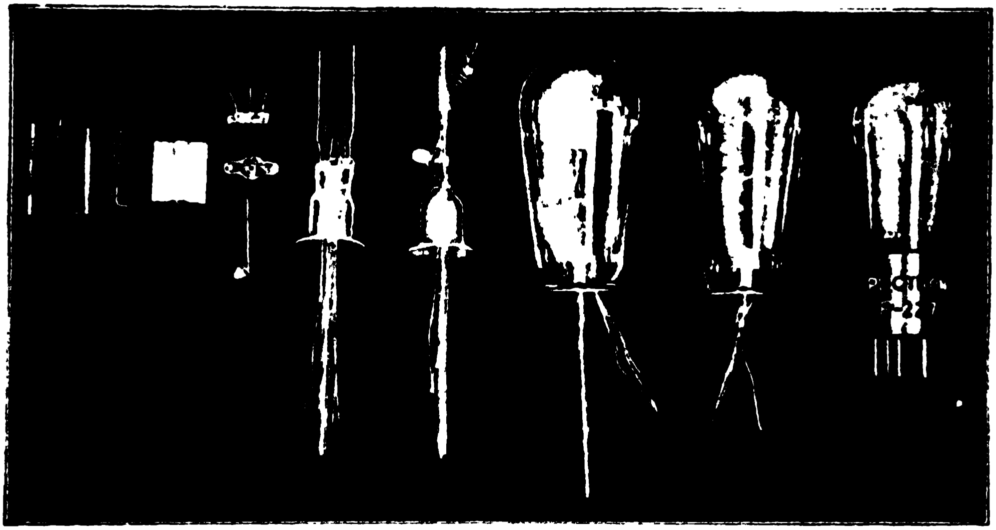


Fig. 220—Elements, and steps in the construction of a 3-electrode indirect heater type tube. At the left are the filament, cathode, grid and plate

employed as a detector, or amplifier and possesses operating characteristics somewhat similar to the 201-A tube which was the standard general purpose tube for many years. Its characteristic curves are shown in Fig. 200. The filament is designed to operate with 2.5 volts at 1.75 amperes, and of course may be heated either with a-c or d-c current, but it is commonly employed with a. c. heating current since other tubes with more desirable heater characteristics are available for d-c filament current operation.

306. Parallel and series operation of heater filaments: When several vacuum tubes of the type just described are operated together, their heater filaments may be connected either in parallel or in series. The parallel arrangement will be considered first since it is most commonly used. At (D) of Fig. 221, the filaments of four separate-heater type tubes are shown connected to the low voltage secondary winding of the

filament heating transformer T. With this type of connection, the secondary winding S of the transformer must deliver a voltage equal to that required by the filaments of the particular types of tubes employed. The current supplied by the transformer winding is equal to the sum of the filament currents taken by all the tubes, so the winding must be of wire having ample cross-section area to carry this current without undue heating or voltage drop. The wiring from the transformer to the tube sockets must also be of ample size to carry the current without excessive voltage

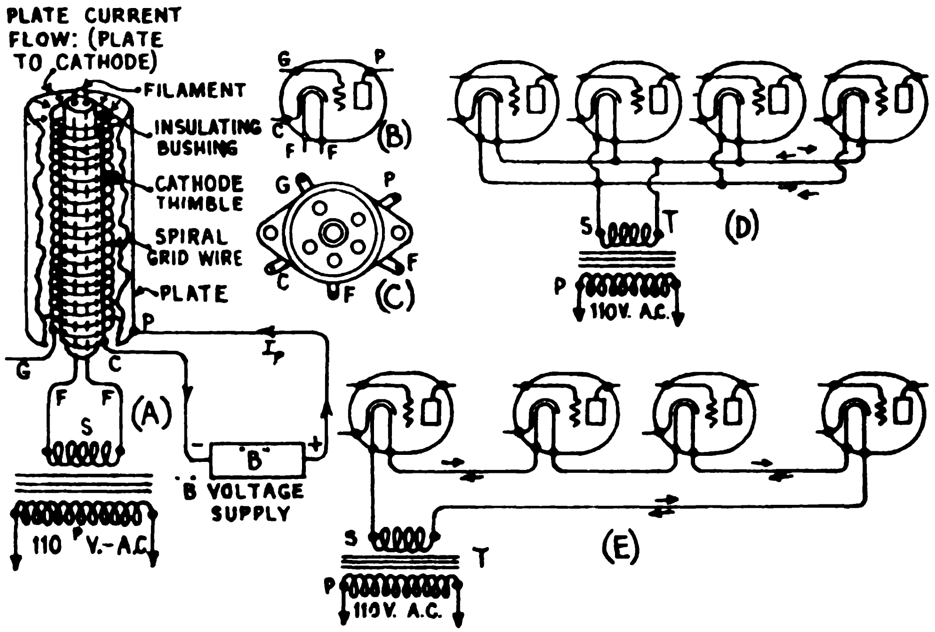


Fig. 221—(A) Construction and arrangement of the elements in a 3-electrode tube of the indirect heater type. (C) 5-prong socket terminal arrangement for the tube. (D) Parallel filament connection. (E) Series filament connection.

drop, in order that the voltage existing at the tube filament terminals shall be of the proper value. Since the corresponding wires carry alternating current, the wires in each pair should always be run close together in order to prevent inducing 60 cycle a-c voltages by electromagnetic induction into other circuits which may run near them. As explained in Article 124, the wires may also be twisted together to prevent induction effects but this is rarely necessary if they are kept close together and at some distance from all other circuits which they might affect. A 5-prong tube socket suitable for tubes of this type is shown at the left of Fig. 222. Sockets of this kind usually contain flexible metal contact springs which press firmly against the tube prongs when it is inserted, thereby making good electrical contact with them. A small step-down transformer designed to furnish low voltage a-c current for the filaments of a-c type

tubes is shown at the right. Transformers of this kind are designed to operate from the a-c house lighting circuit. They are usually of shell-type construction as shown at (D) of Fig. 71. As we shall see later, the filament current in most radio receivers is obtained from the separate low-voltage windings on the same power transformer that is used in the B-power supply unit. A transformer of this type is shown at the left of Fig. 72. A large number of radio receivers manufactured several years ago and still in use, employed types 226, 227, 224, 171-A, 245 and 280 tubes so that four different low voltages are supplied by separate windings on the same core of the transformer. Modern practice is definitely toward the use of tubes having similar filament voltage ratings (2.5 volts in the

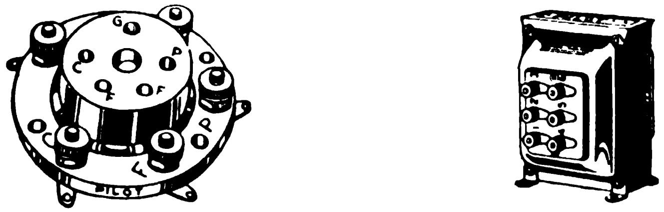


Fig. 222—Left: A 5-prong socket for separate heater type tubes. Right: A small transformer designed to deliver low-voltage a-c current for the filaments of a-c operated tubes

U. S.) so that the filament transformer construction and filament circuit wiring is simplified and cheapened.

If the filaments are connected in series as shown at (E) of Fig. 221, the transformer winding must supply a voltage equal to that taken by one tube, multiplied by the number of tubes. The current in the circuit is simply equal to that taken by a single tube. This arrangement is not used to any extent in a-c operated receivers because it has several disadvantages. If the filament of one tube burns out, all the tubes go out and they must all be tested in order to locate the defective one. Also each filament is at a different potential than the rest. As we shall see, the series filament connection is used in receivers operated from d-c house lighting circuits due to the fact that with this arrangement the total filament current drain is lower than with the parallel arrangement. This makes the series voltage-reducing resistor cheaper to build, since it must not dissipate so much power.

Problem: A radio receiver contains six 235 type tubes connected with their filaments in parallel. The filament of each tube is rated at 2.5 volts and 1.75 amperes. What must be the voltage and current carrying capacity of the secondary winding of the transformer used to supply the current? If the power factor is 1, how many watts of electrical power does the transformer supply to the filaments?

Solution: (a) The voltage delivered by the transformer winding is the same as that required by one tube, i.e., 2.5 volts since it is a parallel circuit. (b) The total current is equal to $1.75 \times 6 = 10.5$ amperes. The winding must be designed to carry this current without undue heating. (c) Since this is an a-c circuit the power is given by

$W = E \times I \times \text{power factor} = 2.5 \times 10.5 \times 1 = 26.25$ Watts. Ans.

Problem: Find the same quantities if the filaments of the tubes are connected in series.
Solution: (a) The total voltage to be supplied by transformer $=2.5\times6=15$ volts. (b) Total current $=1.75$ amperes (same as for one tube). (c) Watts $=E\times I\times$ power factor $=15\times1.75\times1=26.25$ Watts. Ans.

Although many types of tubes are employed in radio receivers at the present time, all of those used as detectors and amplifiers (excepting the last stage audio or "power amplifier" tube) in late type receivers operated from the d-c or a-c electric house lighting circuit, are of the separately-heated cathode type on account of their superior characteristics as regards hum-free operation. They are also used in automobile and aircraft receivers where the more fragile filaments in the directly heated type would break due to the excessive vibration.

307. What the screen-grid tube does: One of the most serious factors which for many years retarded the development of real high-gain vacuum tube amplifiers for amplifying the weak high-frequency (radio frequency) signal voltages set up in receiving antenna circuits, was the fact that in the three-electrode tube, which was the only type commercially available at the time, an excessive capacitance existed between the grid and plate. This caused a feedback of energy from the inductive plate circuit to the tuned grid circuit, with the resulting oscillation and "peanut-stand whistle" so characteristic of the receivers of several years ago. Since the voltage amplification factor of the 201-A type tubes employed in those days is only 8, it was necessary to use several stages of amplification in order to boost the signal voltages up to a reasonable strength. However, as the number of radio frequency stages was increased above about 2, serious difficulties due to oscillation were encountered, and all sorts of circuit arrangements and "oscillation suppression" devices were developed to enable satisfactory operation of 3 and 4 stage r-*f* amplifiers with a reasonable amount of amplification. The popular neutrodyne circuit of old was one of those designed particularly at this stage of radio history, to neutralize the feedback of energy which would otherwise cause oscillation. The development of the screen-grid tube eliminated the necessity for these various oscillation preventatives by simply removing the source of the trouble, in reducing the grid-to-plate capacitance to a very low value, and at the same time made it possible to obtain more amplification per stage due to its higher amplification factor. The fact that the screen-grid principle accomplishes these two important results makes it an exceedingly useful tube. At the present time, the screen-grid tube in one form or another has practically entirely supplanted the older form of 3-electrode tube in radio-frequency and intermediate-frequency amplification, simply because of these important advantages.

308. Feedback in r-f amplifier: In order to understand just how the screen-grid tube greatly reduces the oscillation tendency when used in r-f amplifiers employing tuned-grid and inductive-plate circuits, we must leave our study of vacuum tube construction for a few moments to study the action of an r-f amplifier stage and the way in which a feedback of energy from the plate to the grid circuit can take place due to the grid-

plate capacitance of the tube. Feedback may also take place via other routes but these will be considered in another chapter; at this time we are merely interested in the reason for the particular type of construction employed in the screen-grid tube. In Fig. 223 is shown the fundamental circuit of a tuned radio frequency amplifier stage employing a simple 3-electrode vacuum tube.

L_2C_2 is the tuned input to the amplifier tube, L_3 is the primary and L_4 the secondary of the coupling transformer, which, when tuned by condenser C_4 impresses a voltage E_4 on the grid-filament circuit of the following tube. The small series voltage impressed on the input of the first stage, represented by "e," is impressed magnetically through mutual induction from the primary coil L_1. The circuit L_2C_2 is tuned to resonance with the frequency of this input voltage "e," and when in this condition, presents the minimum impedance to the flow of current circulating through it, indicated by the arrows in the L_2C_2 circuit. The strength of this current at resonance is determined by Ohm's law and is therefore equal to the impressed signal voltage

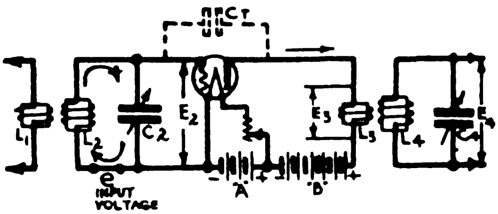


Fig. 223—Fundamental circuit of T.R F amplifier stage using 3-electrode tube

divided by the resistance of the tuned circuit, or e/R. This current in circulating through the inductance L_2, builds up a voltage E_2 across the L_2C_2 circuit, which is the a-c grid potential applied to the tube, and controls the electron flow of the tube. (The voltage E_2 is usually much larger than "e," depending on the size of the inductance L_2 and its resistance.) This important fact has already been discussed in our study of resonance and "gain" in Articles 174 and 249.

The a-c signal voltage E_2 applied to the grid circuit, causes the plate current through L_3 to fluctuate in accordance with the changes it produces in the grid potential. These plate current fluctuations are rather large due to the strong control which the grid has on the electron flow and plate current. The fluctuating plate current flows through the primary of the transformer L_3, which transfers energy to its secondary circuit L_4 by electromagnetic induction, giving rise to voltage E_4 of the same frequency as E_2 but of greater magnitude. This is fed to the grid circuit of the following tube, etc. Since the action in each of the stages in a multi-stage amplifier is similar, we will consider only this one stage. The ratio of E_4 to E_2 is called the voltage "gain per stage" and may be any value between about 2 and 20 (with ordinary 3-electrode tubes), depending upon the efficiency of the design. With screen-grid tubes and properly designed apparatus it is possible to obtain much more gain than this.

Referring to (A) of Fig. 193 and (A) of Fig. 221 it is evident that since the plate, grid and filament are mounted concentrically with each other within the vacuum tube, and since the lead-in wires, tube prongs, and tube socket prongs are close together, some capacitance exists between the elements since they are all at different potentials. Considering a simple 3-electrode tube as shown at (A) of Fig. 224, we find that the grid and plate form a small condenser represented by C_{gp}, the grid and filament form a small condenser represented by C_{gf} and the plate and filament form a condenser C_{pf}. The former one is usually the largest, due to the large exposed area of the grid and the plate, and is the most important one. In a 201-A type 3-electrode tube, the plate-grid capacitance is 10 mmf. In a 227 type separate-heater tube, the capacitances are as follows: grid to plate 3.3 mmf.; grid to cathode, 3.6 mmf.; plate to cathode 2.8 mmf.

None of the internal tube capacitances cause as much trouble as that between the plate and grid. That between the grid and filament or cathode, has the effect of affecting the constants of the grid circuit. Since the value of this capacitance is small, its effect is usually negligible.

The plate-to-filament (or cathode) capacitance is not detrimental since it serves as a very small by-pass for the radio frequency currents to the plate return or negative filament circuit. The presence of the grid-plate capacitance is very objectionable, since it permits the transfer of energy through the tube in the direction opposite to that desired, as we shall now see. The resulting *feed-back* as it is called, is objectionable.

Consider the amplifier stage drawn in simplified form at (B) of Fig. 224. The plate circuit load is inductive. The capacitance between the grid and plate is represented by the condenser and dotted lines above them. Consider an instant when the signal input voltage is in such a direction that it causes a flow of current around the tuned circuit in the direction shown by the solid arrows into the upper condenser plate, making this the positive end of the tuned circuit and driving the grid potential toward positive. This will cause the plate current through L_3 to increase momentarily. The increase of current through L_3 gives rise to a momentary inductive voltage in a direction tending to oppose this increase of current (Lenz's Law) i.e., tending to make the bottom end of L_3 positive with respect to the top end. Since the entire circuit from the grid around to the plate is exactly the same as the simple condenser circuit shown at (C), this voltage impulse is transferred around through the B, A and C batteries and coil L_2, to the grid, causing a small current impulse to flow around to the grid through the circuit as shown by the dotted arrows. (The grid, we must remember, is one plate of the condenser, and therefore this is just the same as the current impulse which would flow in the condenser circuit at (C) from the right hand plate around through the circuit to the left hand plate, if a voltage were set up in L_3 with the polarity shown.) The result then of this current impulse fed back to the grid circuit, is to drive the grid further positive (since it is in the same direction as the original signal current in the tuned circuit and therefore aids it). This added voltage impulse on the grid is amplified by the tube again so as to produce a larger change in the plate current than would otherwise have resulted. Thus we see that the feed-back in the case of an inductive plate load really strengthens the signal impulses and therefore increases their effect on producing changes in the plate current.

A limited amount of feedback is beneficial from the standpoint of amplification, since it tends to increase it. When the next signal impulse takes place a fraction of a

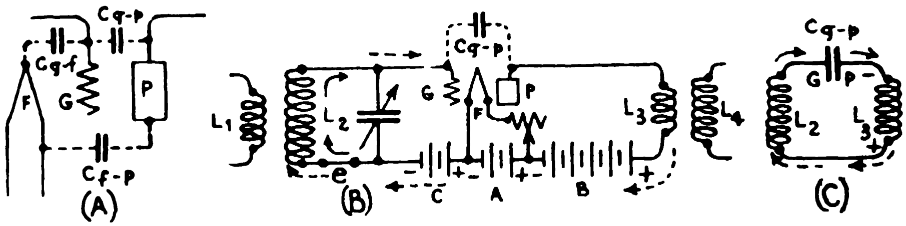


Fig 224—Analyses of feedback in tuned-grid amplifier stage with inductive plate load.

second later, the current flows in the tuned circuit in the opposite direction, the grid is driven more negative, causing the plate current to decrease momentarily. The induced voltage in L_3 is now in the opposite direction and a momentary transfer of current takes place from the grid around the circuit to the plate, thus aiding the signal voltage impulse again. If the grid-plate capacitance is large enough, and the resistance of the circuit through which the energy flows is low so that little of it is dissipated in the form of heat, considerable energy is transferred back and forth through the circuit between the grid and plate during each signal impulse, and the tube will act as a generator or *oscillator*, since each voltage impulse fed back to the grid circuit from the plate circuit is amplified by the tube and fed back again to be amplified again, etc.

If at this time, the input signal voltage due to the primary L_1 were removed, a-c currents would still flow in the tube circuit, because whatever energy came from L_1 originally, has been amplified by the tube and fed back to the grid circuit where it is amplified again, and again and returns to the input. In other words, the tube oscillates, enough energy being supplied from the B battery to make up for all losses of power in the circuit. The frequency of this local feedback energy is determined by the frequency of resonance to which the tuned circuit L_2C_2 is adjusted. If this is varied or adjusted so it is slightly above or below that of the incoming signal, the result is a combination of the incoming signal impulses with the feedback impulses generated in the tube circuit, to produce a third audible frequency impulse whose frequency is equal to the difference between the two, and which sounds like a high pitched whistle; a fourth impulse whose frequency is equal to the sum of the two is also produced. This is too high in frequency to be audible. The former is the whistle heard while an oscillating receiver is being tuned to an incoming signal or when its tuning condensers are not adjusted so as to be exactly in tune with the frequency of the incoming signal impulses. If the load in the plate circuit is either capacitive or a pure resistance, the voltage impulse fed back from the plate circuit to the grid circuit due to the plate-grid capacitance of the tube, is just opposite in phase to the signal impulse applied to the grid circuit. Therefore the circuit cannot oscillate, and the signal output from the tube will be weakened by the feedback. In this case the action is one of *degeneration*.

The remedy for this is obviously either to neutralize this feedback current by an equal feedback current in the opposite direction or phase at every instant; to reduce this current by connecting resistance in the circuit so as to introduce losses, or to alter the internal structure of the vacuum tube so as to greatly reduce or eliminate entirely the capacitance between the grid and the plate. The former method is the basis of the *neutrodyne* system which is no longer used extensively in receiving circuits (since there is no need for it now that screen-grid tubes are available); the next is the basis of the so-called *losser* system, and the last is the method used in the screen-grid tube.

Of course, the grid-plate capacity has a fixed value in any type of tube, whether it is used as an audio or radio amplifier, but the higher frequencies in a radio circuit cause this capacity to be much more effective and troublesome when the tube is used as a radio amplifier. This last trouble alone has probably resulted in the development of more radio circuits and inventions than any other known factor.

309. Electrode arrangement in screen-grid tube: Referring now to (A) of Fig. 225 we have the arrangement employed in the screen-grid tube. This type of tube is made in two forms, one with a directly heated cathode for battery operation, and the other with a separately heated cathode for a-c operation. The construction of both are the same, with the exception of the electron emitter, and for simplicity the former will be considered first. The actions of both in an amplifier or detector circuit are similar, the difference being merely in the arrangement used to obtain the electron emission.

The elimination of the plate-grid capacitance may be understood by reference to the simple condenser circuit at (A) of Fig. 225. G and P represent the two plates of a condenser (we may imagine them to be the grid and plate of a vacuum tube). An a-c generator G is connected in the circuit together with an ammeter A and a voltmeter V as shown. Due to the alternating e. m. f. of the generator, a current (flow of electrons) will circulate around through the circuit, alternately from one plate to the other as shown by the arrows, the current which flows being proportional to the capaci-

tance of the condenser and the voltage V. This becomes evident when we remember that a condenser stores in the plate which is negative, the excess electrons which have been transferred around through the circuit (flow of electric current) by the applied e. m. f. The larger the capacitance of the condenser, the more electrons it can store due to a given e. m. f., and therefore the larger is the electron flow (current flow) through the circuit between the plates. If another plate were placed between these and connected as shown at (B), the effect is now of two condensers in series, but since there is no varying e. m. f. in the circuit between plate S and plate P, and they are connected together by a wire, they will both be at the same potential and consequently, no current will flow between them, current only flowing in the circuit between G and S where the source of voltage is connected. Consequently, the capacitance

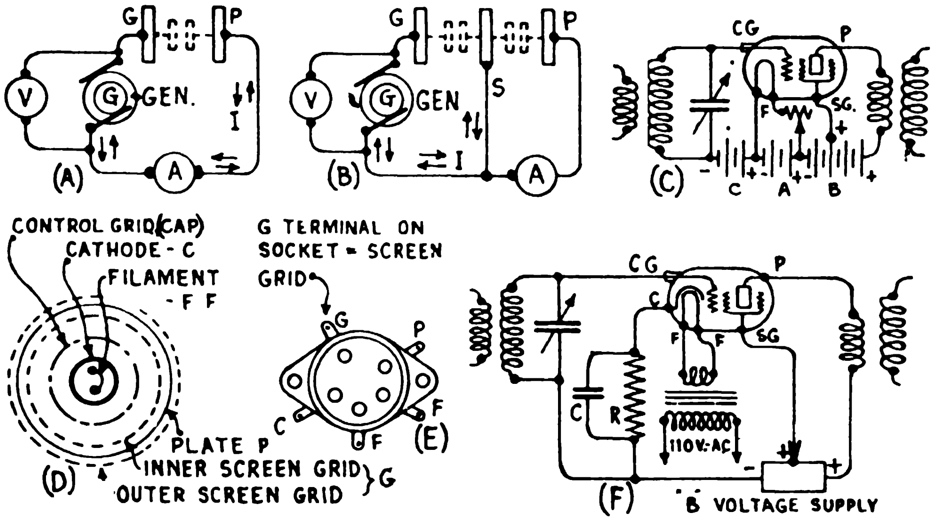


Fig 225—How the plate-grid capacitance in the screen-grid tube is reduced to almost zero by the screen-grid placed between the control grid and the plate. (D) Electrode arrangement in a screen-grid tube. (E) Terminal arrangement. (F) Connection of a-c screen-grid tube in an amplifier circuit.

between S and P has really been shorted out of the circuit and the current indicated by the ammeter drops to zero. We may then say that the effective capacitance between S and P has been reduced to zero by the *electrostatic shield or screen* S, connected as shown. It may be said that P is *shielded* or *screened* from G by S.

In the *screen-grid* type of tube, this method of reducing the capacitance between the plate and grid is employed, by introducing a fourth electrode called the *screen* or *screen-grid*, placed between the ordinary grid and the plate, as shown diagrammatically at (C). The "screen-grid" electrically shields the control-grid from the plate. This form of tube is called a *four-electrode* tube. The ordinary grid, in whose circuit the signal e. m. f. is applied is now called the *control grid* since it controls the flow of electrons between the cathode and plate. Since it is obviously impossible to place a solid sheet of metal between the control grid and plate because it would stop the flow of electrons, a grid-like screen consisting of many turns of fine wire is used, as shown in the cut-open view of the screen-grid tube in Fig. 226, and at (D) of Fig. 227. This is practically as effective in

acting as an electrostatic shield and in reducing the capacitance, as a solid sheet would be. The plate-grid capacitance is not affected by the introduction of the grid bias voltage connected as at (C) of Fig. 225, since the screen is still grounded as regards an impressed a-c signal voltage, that

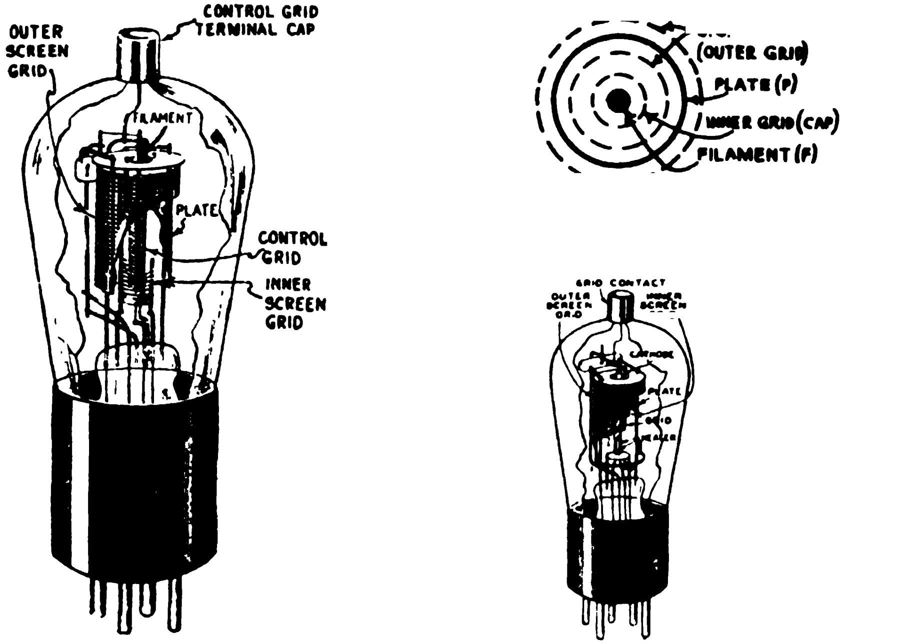


Fig. 226—Left: Arrangement of the elements in a battery operated type screen-grid tube. Upper Right: Top view of the elements in the tube. Lower Right: Arrangement of the elements in a separate heater type of screen-grid tube designed for a-c filament operation.

is, the potential difference between the negative terminal of the C-battery and the screen-grid lead remains steady in value. In addition to the screen directly between the plate and control grid, the outer surface and ends of the plate are screened from the control grid and its lead by a close wire-mesh circular screen as shown in Fig. 226 and at (F) of Fig. 227. The solid sheet metal plate is shown at (E), and the control grid is at (C). To make this construction possible, the control grid lead is brought out to a metal cap sealed into the top of the glass bulb as shown. So effective is this screening, that the direct grid-plate capacitance of the battery type 232 screen-grid tube is .02 mmf., and that of the a-c type 224 tube is .01 mmf., as compared to 10 mmf. for that of the 201-A and 3.3 mmf. for the 227 type of 3-electrode tubes. Of course this very low value of grid-plate capacitance in these tubes reduces practically to zero the feedback due to grid to plate capacitance when they are used as r-f amplifiers. Consequently, there is no instability from this source to hamper the radio-frequency amplifier performance. However, the other sources of feed-

back such as magnetic coupling between the plate and grid coils, coupling in the "B" voltage supply, etc., must also be eliminated in order to entirely eliminate feedback in the amplifier stages, even if screen-grid tubes are employed.

In order to avoid any detrimental action by the screen grid on the flow of electrons through the open spaces in it on their way to the plate, it is maintained at a potential about equal to the stream potential at the point in which it is inserted in the electron stream. This is accomplished by connecting the screen grid to a low voltage tap on the B voltage supply device, usually 50 to 90 volts. The screen voltage may also be made variable by connecting it to the movable arm on a potentiometer connected across the "B" voltage supply. As the voltage applied to the screen is reduced by adjustment of the potentiometer, the mutual conductance of the tube is decreased, with consequent decrease in volume. This arrangement has been used as a volume control for receivers, but it is not entirely satisfactory however, since it may also greatly decrease the selectivity of the receiver.

Since the screen-grid tube consists of the usual 3-electrodes, (grid, plate and cathode), and an additional one, the screen-grid, it is called a four-electrode tube. As the screen grid is maintained at a positive poten-

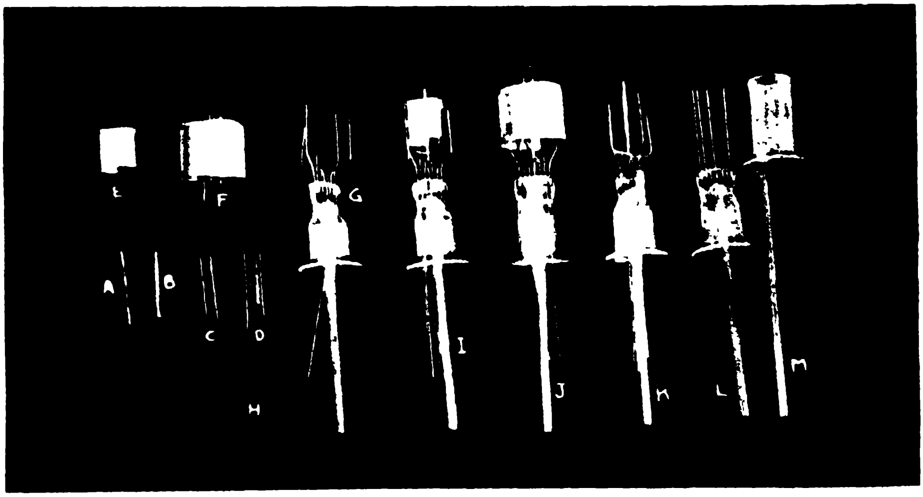


Fig 227—Various stages in the assembly of the main parts of a separate-heater type screen-grid tube.

tial with respect to the heater or filament, it thereby tends to neutralize and decrease the space charge between the filament and plate. This helps to increase the controlling effect of the control grid on the electron and plate current flow, that is, it increases the amplification factor of the tube. Thus, while the 3-electrode 227 type tube has a mu of 9, the 224 screen-grid tube has a mu of about 400, although it is only possible to obtain an

effective amplification of about 40 or 50 in practical circuits. Because of this high voltage-amplification, the wire to the control-grid cap must be shielded from all other wires and circuits if it is long or near them. This is accomplished by using a wire with a copper braid or shield covering connected to ground. The entire tube is also covered usually with a metal tube shield connected to ground. This prevents all stray voltages from reaching the control grid. Also the screen-grid circuit must be well filtered by means of r-f chokes and by-pass condensers, to prevent coupling in the "B" voltage supply.

The electrons from the filament proceed toward the plate and screen-grid at considerable speed, and most of them go through it and are collected by the plate, provided it is kept at a higher positive potential than the screen. Because the screen grid is between the plate and the control grid, the rate at which electrons go across the space is not controlled so much by the plate voltage as it is by the voltages on the two grids, that is, the plate current is more or less independent of the plate voltage within the operating zone of the tube, as shown by the fact that the E_p - I_p curves at (A) of Fig. 228 are almost horizontal, and the a-c plate resistance (which is the ratio between changes in plate voltage and the corresponding changes produced in the plate current), is very high, being 250,000 ohms in the 236 battery type tube and 400,000 ohms for a 224 a-c type of screen-grid tube. Since the plate resistance is almost invariably higher than the load impedance, the plate current is determined mostly by the plate resistance.

310. Types of screen-grid tubes: Screen-grid tubes such as the type 222, 232, and 236 are designed with a thin filament which is heated directly by the d-c current flowing through it. The general construction of this type of tube is shown at the left of Fig. 226. The elements are arranged as already described and as shown at (C) of Fig. 225. At the upper right of Fig. 226 is shown a plan view of the element arrangement looking down on top of the tube. These tubes have four prongs in the base, two for the filament, one for the plate and one for the screen grid. The control grid connection is the cap at the top of the glass bulb as shown.

The elements in the screen-grid tubes such as the 224, 235, 236, etc. designed for a-c operation are arranged in the same way as shown at (D) and (F) of Fig. 225 and the lower right of Fig. 226, excepting that a standard separately heated cathode arrangement similar to that already described and shown in Fig. 219 is employed. The base of the tube has 5 prongs as shown at (E) of Fig. 225. Two prongs connect to the filament, one to the cathode, one to the plate, and the remaining prong which is marked G on the socket, connects to the screen-grid of the tube. The "control grid" terminal is the cap on top of the glass bulb. The heater filaments of several tubes of this type may be operated in parallel from a single transformer winding in the same way, as shown at (D) of Fig. 221.

At Fig. 227 are shown the various elements of a 224 a-c type screen-grid tube during the stages of assembly. A is the filament with small ceramic spacing sleeves, B is the cathode, C is the spiral-wire control grid, D is the spiral wire inside part of the screen grid, E is the plate, F is the metal mesh outside part of the screen grid. At I, the plate, control grid, and cathode assembly are mounted on the stem. At J, the outer and inner parts of the screen-grid have been slipped over the plate. The various detector and radio and audio frequency amplifier circuits in which screen-grid tubes may be used will be studied later.

311. Characteristics of screen-grid tubes: Some of the static characteristic curves of an a-c screen-grid tube are shown at (A) of Fig. 228. It will be noticed that over the normal operating range of plate voltage down to about 90 volts, changes of plate voltage have little effect on the plate current. At low plate voltages, the current actually decreases instead of increasing, that is, an *increase* in plate voltage causes a *decrease* in plate current. The tube then has a *negative* resistance characteristic. This is very important in the action of the tube as a "Dynatron". At plate voltages lower than the screen-grid voltages, electrons may get through the screen-grid, but when they strike the plate they dislodge electrons (secondary emission) and both are attracted back to the screen-grid, because of its greater positive potential. This backward flow of electrons opposes the normal flow of electrons in the tube, thereby causing the plate current to decrease.

When used as an amplifier, the plate, grid-bias and screen-grid voltages are adjusted so that the tube is operated on some portion of the almost flat part of its plate-voltage plate-current curve. The sum of the currents in the screen-grid circuit and the plate circuit are almost constant. The 232 and 224 types of screen-grid tubes may be operated either as amplifiers or detectors as we shall see later.

312. Space-charge grid arrangement: The amplifying effect of a tube is due to the fact that since the grid is closer to the filament than the plate, a slight grid potential change, causes a greater plate current change than an equal plate potential change would. The amplification factor of an ordinary 201-A type tube is about 8.

The space around the filament is filled with a cloud of negative electrons, which constitute a space charge. This negative cloud repels the negative electrons attempting to shoot out from the filament, and being closer to the filament than is the grid, it has a greater effect than the grid. The space-charge produces two effects on the operation of the tube:

The space charge constitutes a constant opposition to the attraction of the positive charge of the plate for the negative electrons from the filament. To overcome this constant repulsion, nearly 85 per cent of the plate potential applied to the ordinary 3-electrode tube is used up (this part of the plate potential being practically useless as far as amplification goes), leaving about 15 per cent for direct action on the filament to establish the plate current and produce amplification. It is evident then that if the space charge could be entirely eliminated, for equal results, the plate voltages necessary for tube operation would be only about 15 per cent of what they are with 3 electrode tubes, and the plate supply voltage unit would be very much simplified and cheapened.

The second effect of the space charge is to lower the amplification constant of the tube, since the grid does not have perfect freedom in controlling the plate current flow. In practice, the tube is always operated with the grid negative. As the repelling effect of a negative grid is added to the existing repelling effect of the space charge, any small change in grid potential is only a small percentage of the total repelling potential. That is, if the space charge were eliminated, the grid effect would be many times what it is with the space charge present, and (with nothing else happening) the amplification factor of the tube would be raised from eight up to 30 or 40, without any change in plate impedance.

Of course, the amplification factor can be increased as is done in ordinary high-mu tubes by increasing the fineness of the grid mesh and placing the grid relatively nearer

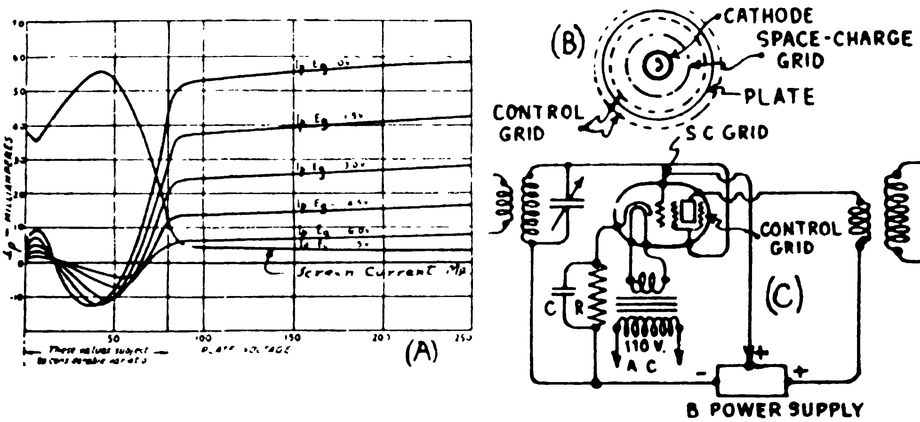


Fig 228—(A) Average static characteristics of a '24 type screen grid tube
(B) Arrangement of elements when the space-charge connection is used
(C) Connection of an ordinary screen-grid type tube as a space-charge grid tube in a circuit

to the filament than the plate. But this increases the plate to grid capacity enormously and increases the plate impedance, thus making these tubes usable only in audio-frequency circuits, due to the difficulties brought about by excessive feedback when used at the high frequencies existing in radio-frequency circuits, and the difficulty in securing the proper high impedance load necessary in the plate circuit of the interstage coupling device to obtain any appreciable gain. If an ordinary 3-electrode high-mu tube such as the type 240 were to be constructed to have a mu of 200, the plate impedance would be about "*six million*" ohms! The effect of the space charge in ordinary three-electrode tubes is far greater than the effect of the grid, and is a constant factor unaffected by the incoming signal, and tending always to reduce the amplification of the tube.

The space charge effect can be overcome, or at least reduced partially, by putting a *positive charge at or near the region where the negative space charge accumulates.* This is done by introducing a positively charged fourth electrode into the tube, whose purpose it is to assist the work of the plate in attracting electrons and do this efficiently because of its being nearer the troublesome cause. It is evident that this fourth electrode must surround the filament, can be placed either between grid and filament or between grid and plate, and must be of open construction to permit the electrons to fly through it. It can be in the form of another grid, an open winding or a network. If this electrode is placed around the filament, between it and the ordinary control grid as shown at (B) and (C) of Fig. 228, the tube is known as a space-charge grid tube.

The ordinary screen-grid tube can be connected up as a space-charge grid tube as shown at (B) and (C) of Fig. 228. The inner or control grid of the screen-grid tube now becomes the space-charge grid and the screen-grid of the screen-grid tube now becomes the control grid as shown. The space-charge grid is maintained at a positive potential by connecting it to a low voltage tap on the "B" power supply unit.

The practical results of the space-charge grid connection are, that the plate current for a given plate voltage is much increased and the mutual conductance of the tube is also increased. Since the screening effect of protecting the grid from potential variations in the plate circuit is lost by this arrangement, the grid-plate capacitance has reappeared, and therefore the tube is of no use as a radio-frequency amplifier. It is in audio-amplifier circuits that the space-charge grid tube finds its field of usefulness and a very high amplification per stage can be obtained at audio frequencies. However, because of the rather high internal tube capacitances resulting from this connection, the space-charge grid tube tends to discriminate against the high-frequency audio tones when used as an amplifier. Audio amplifier circuits for the space-charge grid tube will be considered later.

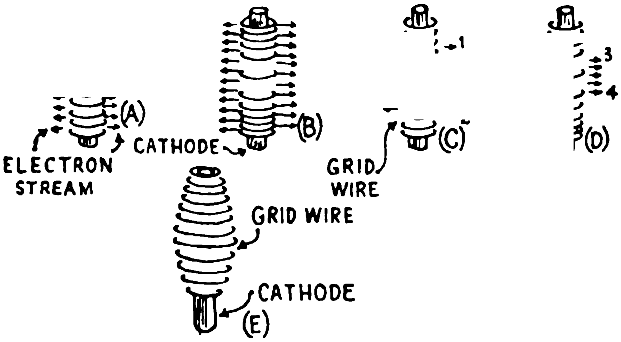
313. Variable-mu (super-control) tube: A detailed study of the uses and fields of application of the variable-mu tube will not be presented at this point since we have not yet progressed sufficiently in our study of radio-frequency amplification to appreciate the full significance and importance of what it accomplishes. This phase of the study will be considered later when dealing with radio-frequency amplification. At this time we will consider merely the constructional f atures which enable us to build a vacuum tube whose amplification factor and mutual conductance may be made to vary in any desired steps when the control grid potential is varied.

In the ordinary screen-grid form of vacuum tube already described in Articles 309 to 312, the control grid is composed of a small spiral-wound coil of wire of uniform diameter with uniform spacing between the turns as shown at (A) of Fig. 229. Obviously, every portion of a control grid of this kind has an equal effect on the control of the flow of electrons through the open spaces, when it is placed around a cathode emitting electrons uniformly from its surface as shown. The E_g - I_p characteristic curve of such a tube is shown by curve K at (A) of Fig. 230. It is evident that the characteristic is practically a straight line for the normal control grid potential working range from points *o* to *a* (from o to about —5 volts). Therefore, over this range the plate current changes are substantially proportional to the changes of control grid potential. (We need not consider the part of the characteristic for *positive* control-grid potentials, since amplifier tubes are never operated with positive grid potentials.) As the control-grid potential is made more negative toward points *c* and *b*, the plate current changes are no longer quite proportional to control-grid potential changes, as shown by the fact that the characteristic becomes somewhat curved. When the control grid potential is about 11 volts negative, (point *b*) the electron flow through it is entirely stopped by its negative charge, so the plate current drops to zero as shown. The curve L in (B) of Fig. 230 represents the control grid potential—mutual conductance curve for the 224 tube operated at normal filament, plate and screen-grid voltages. It will be seen that the mutual conductance also drops to zero when a negative grid potential of about 11 volts is reached. It will be remembered from our previous study in Article 287, that the *mutual conductance* of a vacuum tube is defined as the change in plate current produced, divided by the change in grid potential producing it.

If any of the electrodes of the tubes are not arranged symmetrically with each other, the operating characteristics may become quite different. For instance, in the variable-mu screen grid tube developed by Stuart Ballantine and H. A. Snow, the individual turns of wire on the control grid are not uniformly spaced as at (A) of Fig. 229, but are more widely spaced

at the middle than at the two ends, as shown at (B). It is evident that with this construction, the more closely spaced end portions will oxert a greater controlling action on the flow of electrons through them than the more openly spaced center part will.

At low negative grid bias voltage, the effects of a non-uniform turn-spacing on the electron flow and the tube characteristics are practically similar to those obtained when a uniform grid structure is employed. Electrons get through uniformly all along its entire length, as shown at (B). The screen grid and plate are not shown in these sketches in order to avoid confusion. It should be remembered that the positive plate surrounds the control grid, tending to draw the negative electrons through it. As the grid bias voltage is made more negative however, the electron flow from those areas



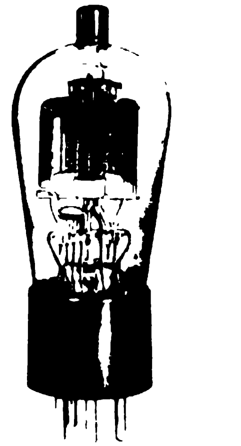


Fig. 229—How the non-uniformly spaced control grid wires in the variable-mu tube passes electrons at the widely spaced portion and acts as an impassable barrier at the closely wound portions (E) A possible control-grid shape which gives the same results but which is not practical to manufacture Right An open view of a variable mu tube

Courtesy R.C A Radiotron Co

of the cathode covered by the closely-wound portion of the grid is gradually cut off, since the negative charge of these grid wires form an impassible barrier for the negative electrons. When this condition occurs, only the smaller area of the cathode around the more widely spaced turns between points 1 and 2 is effective as shown at (C), since electrons can get through the more open mesh there. Therefore, the amplification factor and mutual conductance of the tube are decreased rather abruptly at this point since given changes in grid potential now produce smaller changes in the electron flow and plate current than when the entire grid is acting on the electron flow; because the ends of the grid are already cutting off the flow of electrons, so no change in electron flow results there. For greater negative grid potentials, the electron stream is still further reduced, until a point is finally reached where the entire plate current flow is reduced to zero.

The variations in plate current of the commercial 235 variable-mu screen-grid tube of this type for various grid potentials is shown by curve V, at (A) of Fig. 230. The mutual conductance is found to vary similarly as shown by curve M at (B) of Fig. 230. Notice that both the plate current and the mutual conductance (transconductance) increase rather abruptly after a certain point is reached in each case. This is the reason for the name *variable-mu* or *multi-mu* tube. Referring to curve V at (A) it is seen that the slope of the E_g - I_p curve is rather steep from point z to point m. Since the slope of this curve is a measure of the amplification factor of the tube (see Article 288) the amplification factor is high for a grid potential range represented by this portion of the characteristic. From point z to point x, the characteristic is very curved so the slope and the mu is changing rapidly. From x to e the characteristic is practically a straight line again, with a much smaller slope than before. Thus the mu for the grid potential range represented by this part is very much smaller than before. Consequently, if the normal operating potential of the grid of this tube is shifted from say, -6 volts to -24 volts by the application of a greater negative grid biasing voltage.

the amplification factor and mutual conductance would drop considerably. For instance, in the 235 type variable-mu tube with a fixed plate voltage of 250 volts and a fixed screen-grid voltage of 90 volts, the mutual conductance is 1 micromho at a control grid potential of -50 volts, 15 micromhos when it is -40 volts, and 1050 micromhos when it is -3 volts (see curve M at (B) of Fig. 230).

This important characteristic of being able to greatly vary the *mutual conductance* and *amplification factor* of a variable-mu tube simply by changing the control-grid bias voltage (either by a "manually-operated volume control" or by an "automatic volume control"), makes it possible for the tube to handle a larger range of signal strength or voltage without distortion due to cross-talk and cross-modulation (see Art. 362), than an ordinary screen grid tube can. When a weak signal is being received,

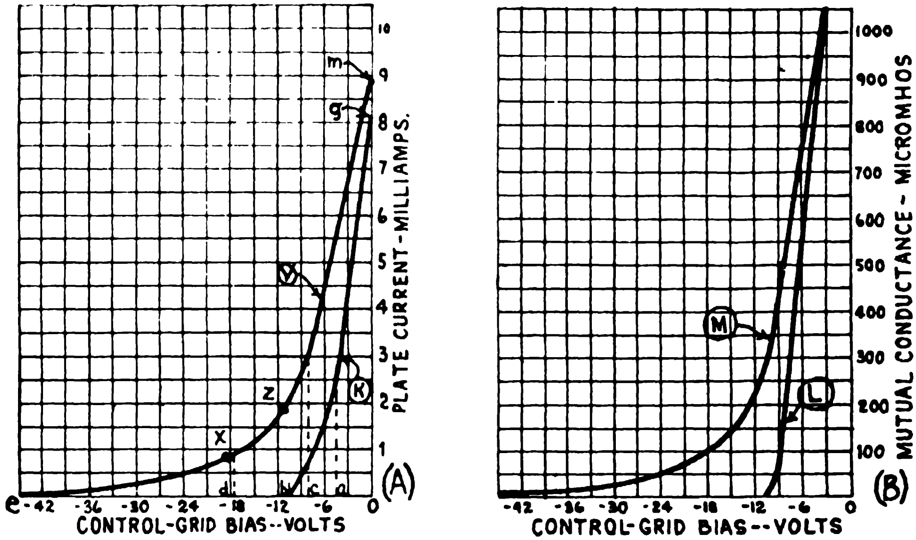


Fig. 230—(A): Eg-Ip characteristics of a '24 type screen grid tube (K) and a variable-mu (or "super-control") type of tube (V).
(B): Eg-Gm characteristics of the same tubes. Curve (M) is for the variable-mu tube and curve (L) is for the ordinary screen grid tube.

high amplification is desired, and the volume control of the receiver is adjusted so as to apply a reduced negative bias to the control-grid, thus permitting the tube to work over the high-amplification region between *z* and *m* on characteristic (V) of (A) of Fig. 230. When a powerful signal is being received, the volume control is adjusted so as to make the grid bias voltage more negative, thus shifting the operating region toward *x* and *e* on the characteristic. This higher negative bias causes the electron flow from the sections of the cathode enclosed by the ends of the control-grid to be cut off (see (D) of Fig. 229), thus greatly reducing the control effect of the grid on the electron flow, that is, reducing the "amplification factor".

In addition to this convenient variable amplification feature, the variable-mu tube is also important because as will be seen from the curves in (A) of Fig. 230, it can handle a much larger range of signal strengths or voltages applied to its control-grid than can an ordinary screen grid tube. For these reasons, variable-mu tubes are often called *super-control* amplifier tubes. They are particularly suitable for use in sets having "automatic volume control" (see Art. 376).

The 235 type variable-mu tube shown in Fig. 229 is of the screen-grid separate-heater type, since it is designed to be used in the r-f or intermediate frequency amplifiers of a-c operated receivers or as the "mixer" tube in super-heterodyne receivers. The wide spacing of the control grid at the center and the closer spacing at the ends may be seen from this

illustration, since the outer screen-grid and plate have been partly broken away to show the inner screen grid and control grid. Otherwise the construction of the tube is exactly similar to that of the screen-grid 224 type. The special applications of the variable-mu tube will be considered in connection with cross modulation in Art. 362, and radio-frequency amplifiers. It is important to note that the change in the characteristic of the tube can be made to take place at any pre-determined operating condition merely by proper design and spacing of the electrodes.

314. Power tubes: In all the amplifying tubes except the last one in the audio amplifier, the object desired is an amplification or increase of the *signal voltage* applied to the input circuit. The varying signal voltage acts upon the grid of the tube to control the plate current. The varying plate current flowing through a resistance or inductive load produces varying potential difference or voltage drop across the load. The variations in voltage appearing across the load are greater than the variations in signal voltage applied to the grid, i.e., the applied voltage variations are amplified.

In the output circuit of the amplifying tube in the last audio amplifier stage (the tube that feeds energy to the loud speaker), it is electrical *power* (watts) that is desired, since actual electrical power is required to operate the speaker and cause motion of its diaphragm. Therefore, it is desirable that the last tube not only have a high amplification factor, but that it also have a large plate current and low plate impedance so that only a small part of the energy supplied to its plate circuit by the "B" power supply device be used up in the tube itself, and most of it be transferred to the loud speaker coupling device connected in its plate circuit. If a large portion of the applied plate circuit voltage is used up inside of the tube to overcome the impedance of the plate—cathode path, then very little will be left for use in supplying power to the loud speaker circuit since ($W = E \times I$). Also since the signal voltage set up in the antenna circuit has been amplified many thousand times by the various amplifying stages of the receiver before it reaches the grid circuit of the last tube in the receiver, this tube must be capable of handling without distortion, quite large variations of signal voltage applied to its grid circuit (as high as 50 volts or more in home radio receivers and even more in high power audio amplifiers), that is, its E_g - I_p characteristic curve must be straight over a large range of grid potential.

Since in the power tube it is desired to obtain as much power output as possible due to a given applied signal voltage, the term *power sensitivity* is commonly used when comparing power tubes. The "power sensitivity" is a measure of the power controlled in the plate circuit by a given input grid voltage change. Thus in a tube with a large "power sensitivity" small changes of grid potential handle large changes in output power Obviously this property is very desirable in a power output tube. Power sensitivity will be discussed more in detail in Article 319 in connection with the power pentode tube. Since these special requirements are somewhat different from those desired for interstage amplifier tubes, the tubes used in the last audio stage of radio receivers and audio amplifiers are constructed somewhat differently from the ordinary general-purpose amplifying tubes, and since their function is to deliver as much undistorted power to the loud-speaker as possible, they are called *power tubes*. If we study the methods by which these characteristics must be obtained in an ordinary 3-electrode type of tube, we will see that the requirements con-

flict so that it is not possible to attain all of them, but that a compromise in the resulting characteristics must be accepted.

First, in order to obtain a low plate impedance, the plate must be mounted rather near to the cathode (electron emitter) so as to make the length of the plate current path short, and the plate area may be made quite large so as to make the cross-section area of the electron stream large. Also, the cathode must be designed to provide a plentiful supply of electrons. Second, in order to obtain a high amplification factor, the grid wires may be very closely spaced as shown at (A) of Fig. 231 and the grid

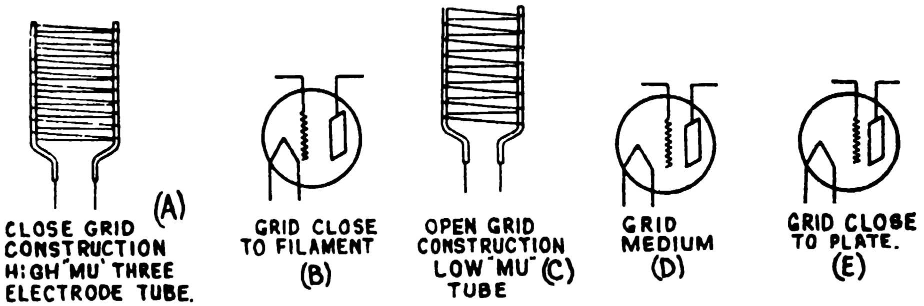


Fig 231—Effect of grid position and structure on the amplification factor and plate impedance of a 3-electrode tube

should be mounted much nearer to the filament than the plate is, as shown at (B), so that a given change in grid potential will have a greater control on the electron flow than an equal change in plate potential would. It can be seen that these two requirements conflict, since if the plate is mounted close to the filament to reduce the plate impedance then the grid would have to be mounted practically on the filament to produce a high amplification factor. This would be undesirable due to the possibility of short circuits. Also if the grid wires were of very close mesh, the grid would entirely cut off the flow of electrons for rather small values of negative grid potential and the E_g - I_p characteristic would quickly drop down to zero plate current and therefore would not be straight for a very long portion, i.e., only rather small input signal voltages could be applied to the grid circuit without distortion.

As a result of these considerations, our 3-electrode power tubes such as the 171-A, 245 and 250 types are compromises between the desired characteristics. In order to secure the desirable low plate impedance in the neighborhood of 2,000 to 6,000 ohms, together with a grid characteristic such that the E_g - I_p characteristic is practically a straight line over rather a large swing of grid potential, the grids of such tubes must be wound rather openly as shown at (C) and must be placed quite far relatively, from the filament as shown at (D). If the grid is too near to the plate, as at (E) the grid will have no greater effect on the plate current flow than the plate has, and the amplification factor will be low. The result is, that such tubes have a rather low voltage amplification factor as will be seen from the following figures for some common American 3-electrode power tubes.

Tube Type	Permissible signal grid-voltage swing (volts)	Maximum undistorted output (milliwatts)	Plate impedance in ohms	Plate current (M. A.)	Voltage amplification factor
120	22.5	110	6,300	6.5	3.3
231	22.5	170	4,000	8 .	3.5
112-A	15	260	5,000	7.6	8.5
171-A	40.5	700	1,850	20	3.0
245	48.5	1600	1,750	34	3.5
210	35	1600	5,000	18	8.0
250	38	4600	1,800	55	3.8

Note: These figures are those for the condition where the tube is operated at maximum plate voltage and correspondingly proper negative grid bias voltage. They are taken from the table of Fig. 214.

Examination of these values shows that in general, those power tubes having the lower plate impedances and larger power output values have the lower amplification factors. It is also evident that the larger tubes such as the 245, 210 and 250 types can handle a larger signal voltage swing and deliver more undistorted power output than the smaller types. As their plate currents are quite large and they employ quite high plate voltages, considerable power is dissipated in the plate-filament circuit of such tubes.

315. Filament current supply for power tubes: The filaments of all 3-electrode type power tubes, with the exception of the 120 and 210 types (which are no longer used to any great extent), are of the oxide-coated ribbon type. The filaments of the larger power tubes such as the 171-A, 245, 210 and 250 types are rather thick and consequently if they are heated with alternating current, their temperature will not vary to any great extent over each a-c cycle since they retain considerable heat. They are therefore heated with a-c of the proper voltage supplied by a step-down transformer, and a center-tapped resistor is connected across the filament for obtaining the electrical center of the filament as explained in Article 303. The method of obtaining the grid-bias voltage automatically will be explained later. Heating the filament of a power tube with a-c produces some 120-cycle ripple in the plate current, as in the case of any of the other tubes in the receiver. A slight ripple in the plate current will produce a slight hum in the loudspeaker, but this will not be audible a foot or two away from the loud speaker. Of course, the power tubes designed for use in battery-operated receivers have their filaments heated from the "A" battery.

316. Heating of the plate: The electrons which are travelling from the filament to the plate are moving at the rate of thousands of miles per second when they hit the plate. When electrons moving at such a high velocity are suddenly stopped by the plate, their energy of motion is suddenly converted into heat which is given up to the plate. This continuous bombardment of the plate by the stream of electrons attracted to it, results in considerable heat being produced in it especially if the plate current is large (large number of electrons moving to the plate every second) and a

high plate voltage is employed (greater velocity of the electrons when they strike the plate). As will be seen from the table above, these are just the conditions which are present in power tubes, especially in the larger ones such as the 245, 210, and 250 type.

The rate at which the heat is developed in the plate, for a non-oscillating tube, is proportional to the product of the plate current and the plate voltage. Since the plate is in a vacuum inside the glass bulb, this heat can be dissipated most by *radiation,* (actually a small part is also dissipated by conduction through the metal plate supports and glass stem). It is a well known law of physics that a black rough body will radiate heat much better than a smooth polished surface, when hot. Therefore the heat radiating properties of the plates of power tubes are increased by coating their surfaces with a rough black carbonized surface layer. This may be produced by spraying them with a solution containing graphite, or by depositing lampblack on them by exposing them to a luminous gas flame during manufacture. Inspection of a 245, 210 or 250 type power tube will reveal this blackened plate. This makes possible the use of a plate of smaller size, for equal heat radiation.

317. Need for the pentode tube: Examination of the characteristics of the various 3-electrode power tubes listed in Fig. 214 shows that in general these tubes do not deliver a very great amount of undistorted power (remember that the figures given in the chart are for the power in *milliwatts*), when we consider that such high plate voltages as specified are applied to the tubes and such large plate currents flow.

For instance, from Fig. 214 we find that a 245 type power tube with 250 volts applied to the plate, has a plate current of .034 amperes flowing and delivers an undistorted power output of 1600 milliwatts (or 1.6 watts). Now the electrical power being supplied to the plate circuit of this tube by the "B" voltage supply device is equal to $W = E \times I = 250 \times .034$ or 8.5 watts. The tube only delivers 1.6 watts of useful power or about 1/5 as much as we put into its plate circuit. The rest is converted into useless heat in the plate-to-cathode circuit. There are two reasons for this, and when we know what they are, we will understand just why and how the pentode tube differs from other types of tubes.

Various forms of pentode tubes have been employed in Europe for several years because of the necessity for economical operation of the many battery operated receivers used there. It is essential in equipment of this kind that the plate voltages employed on tubes be as low as possible and that the amplification produced by each tube be as high as possible in order to economize on battery and tube cost. Also, since in most European countries radio set owners are taxed for radio reception on a basis of the number of tubes employed in the receiver, it is essential that each tube be made to produce as much amplification as possible in order to obtain the necessary amplification with a minimum number of tubes. The pentode type of tube fulfills these requirements by providing the same amplification and power output at lower plate voltages (or more amplification and power output at the same plate voltages) than is possible with present forms of 3 and 4-electrode tubes.

Let us now see what undesirable tube characteristics the particular construction of the pentode tube reduces or eliminates. Before proceeding with this study it is important to point out that pentode tubes are five-electrode tubes, but that there are two entirely distinct forms of pentodes or "five-electrode" tubes. One is the *power pentode* and the other is the *screen-grid pentode.* Each has five electrodes, but as we shall see

these electrodes are arranged differently inside the tube resulting in characteristics which differ. The power pentode tube is a low-resistance (comparatively) high-output tube designed only for the final stage in an audio amplifier. It is not suitable for use in a radio-frequency amplifier. The other pentode is a high-resistance, low-power output tube designed for radio or audio amplification only; it is of the screen grid type. It is not suitable for use as an output tube.

318. Secondary emission and space charge reviewed: Although secondary emission and space charge were explained in Article 266 and

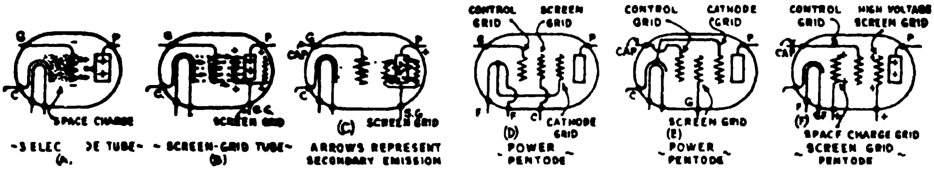


Fig 232—Development stages of the power pentode and the screen grid pentode tubes.

309, a complete understanding of them is so important in the study of the pentode tube that they will be reviewed briefly again here.

The effectiveness with which a vacuum tube amplifies, depends upon the effectiveness with which the potential changes on the grid affect the plate current or the electron stream flowing between the cathode (or filament), and the plate. This variation in the plate current is caused by a variation in the negative charge existing between the filament and the plate. As this charge is increased negatively—for instance, by adding additional grid bias or by applying the negative half of an alternating signal voltage cycle—the plate current is decreased, the stronger negative charge repelling more electrons seeking a path through the grid to the plate

The negative charge existing in the space between the filament and the plate of an ordinary vacuum tube consists of two parts, the useful control charge imposed by the grid, and the space charges of the cloud of electrons which are in the space between the cathode and the grid at any instant as shown at (A) of Fig. 232. This negative charge will tend to repel any other electrons which tend to come off from the cathode. The existance of this space charge detracts from the effectiveness of grid potential variations in the same manner that a glass full of water added to, or taken from, that in a large reservoir has a negligible effect on the total, compared with that of the addition or withdrawal of this same amount from a small pan of water. It is obvious that if we could eliminate this negative space charge, the effect of grid potential variations on the electron flow between the cathode and plate would be considerably increased, that is the amplification factor of the tube would be raised. This is exactly what the fourth-electrode, (the screen-grid) accomplishes in the screen-grid tube, by introducing a counteracting positive charge behind the control grid. Some electrons strike this screen grid and current will therefore flow in its circuit. The power wasted in its circuit is small however, because this grid is a coarse mesh and only comparatively few electrons stick to it. The rest are speeded up so much by the accelerating force of its positive charge, that they go rushing through it at speeds as high as twenty thousand or more miles per second, to land on the positive plate behind it as shown at (B). In the space-charge grid connection shown at Fig. 228, the positive charge is introduced *between* the cathode and control grid so it is even more effective in neutralizing the space charge which is normally between the cathode and control grid.

As soon as the space charge is reduced or eliminated, the effectiveness of the plate voltage is also increased of course, since electrons emitted from the filament do not have to overcome the opposition of the space charge when on their way to the plate.

The effect of the space charge could also be reduced by using very high positive plate voltage, but in the 3-electrode tube it would require a rather excessive plate voltage to overcome the effect of space charge. By using the screen grid or space-charge grid, we can achieve the same effect with much lower plate voltages, or using the same plate voltages, we can obtain a great increase in operating efficiency, that is, in amplification factor.

The use of the screen grid or space-charge grid arrangement seems like a very simple way to get rid of the space charge, but unfortunately the effectiveness of the screen grid tube (particularly as a power amplifier), is limited by secondary emissions caused by the bombardment of the electrons against the plate.

As the electrons, which are moving at velocities of thousands of miles per second, strike the plate, they not only give up their kinetic energy in the form of heat, but also tend to forcibly knock other *secondary* electrons out of the plate. This is called *secondary emission.* It is possible for a single electron to knock quite a few electrons loose from the plate, depending on its velocity. In the ordinary 3-electrode tube these secondary electrons may float around for a fraction of a second and either return to the plate or join the space charge. In the screen-grid tube however, the presence of the highly positive screen grid may attract these secondary electrons and get them moving with sufficient velocity to get away from the field of the plate, and into the positive field of the screen grid as shown at (C), taking a direction exactly opposite to that of the negative electrons leaving the cathode and therefore interfering with their motion (like charges repel) and causing the plate current to decrease. Since one electron may knock out as many as 20 electrons from the plate, if enough secondary electrons are knocked out, the number leaving the plate may be greater than the number arriving from the cathode. In this case, the main electron flow is from plate to screen-grid, that is, the plate current flows backwards. This is shown in the E_p - I_p characteristic curves of a screen grid tube at (A) of Fig. 228. It will be seen that when the plate voltage is less than the screen grid voltage (screen grid voltage for this tube was 75 volts positive), the plate current flows from plate to screen-grid, as shown by the fact that the plate current curves dip down below the zero plate current line, i.e., go in the negative direction. This is the reason for these peculiar bends in the characteristic curves of a screen grid tube. This part of the curve represents a condition of the tube that makes it worthless for the purpose of linear amplification. To prevent this of course, the plate should always be operated at a potential at least equal to that of the screen-grid, preferably higher. This means that even though we gain the advantage of reduction of space charge by using the screen-grid, it speeds up the electrons so much that they cause secondary emission which prevents us from being able to reduce the plate voltage to a value near that of the screen-grid voltage.

Now we are prepared to see just what the additional or fifth electrode in the pentode tube does.

319. The power pentode tube: The introduction of another grid forming the *pentode* or *five-element* tube effectively reduces the secondary emission, making it possible to take practical advantage of the increased amplification due to the screen grid. In the usual form of power pentode, the third grid is connected inside of the tube to the cathode and is commonly referred to as the *cathode grid* or *suppressor grid* since it "suppresses" the secondary emission.

In the direct heater type power pentodes such as the 247 and 233 types, the cathode grid is connected directly to the center of the filament inside the tube as shown at (D), and a standard five prong UY socket is employed with the terminals arranged as shown in Fig. 232. In the separate-heater type power pentode tubes such as the 238 type, the cathode grid is connected directly to the cathode as shown at (E). Therefore no extra external connection is necessary for it. A five prong UY socket is also employed for this type of tube, with the terminal arrangement shown. The control grid terminal is the cap on top of the tube. At the right of Fig. 233 is shown a direct

heater type of power pentode with a portion of its plate cut away to show the interior construction and arrangement of the elements. The arrangement of the elements may be seen more clearly from the drawing at (A). This type of tube is designed for use in the output stage of home radio receivers operated from the a-c electric light line.

In pentode tubes the screen grid is sometimes referred to as the *high voltage grid.* This is probably a better name for this element than "screen-grid" because in the power pentode tube the primary purpose of this grid is to accelerate the electrons toward the plate and not to screen

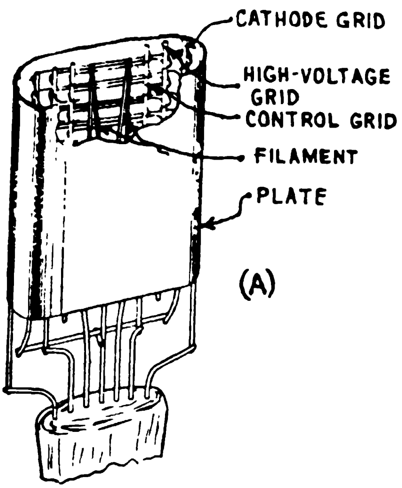


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Fig. 233—Left: Skeleton sketch showing the arrangement of the elements in a power pentode tube
Right: A power pentode tube designed for a-c filament operation. The plate is broken open to show the interior construction

the input from the output circuit as in the case of the screen-grid tube.

The cathode grid, forms a grounded shield between the plate and the screen grid. As it is at the same potential as the cathode, it has practically no effect on the electrons that have just left the cathode en route to the plate. However, its negative potential, in reference to the plate, is that of the instantaneous plate voltage, with the result that the *secondary* electrons prefer returning back to the plate rather than passing through the cathode grid to get to the screen grid beyond.

An electron leaving the filament then, first comes into the field of the control grid (see (D) of Fig. 232) which will have a certain negative charge. It is drawn through this grid by the positive charge on the plate and screen grid beyond. It next comes into the field of the positive screen grid and is either attracted to it and neutralized, or is speeded up sufficiently so it goes through the screen grid to the cathode grid. It may be retarded by this grid because it is at zero potential. At any rate it is being attracted strongly by the positive charge on the plate just beyond, so it goes through the cathode grid and strikes the plate. If it knocks another electron out, or if it rebounds, it goes back a short distance and is immediately repelled back to the plate by the cathode grid and at the same time attracted back to the plate by the positive charge. In other words, any rebounding electrons or secondary electrons will be attracted back to the plate where they are useful.

The characteristics of the power pentode tubes types 238, 233 and 247 will be found in Fig. 214. The 238 type employs a separate heater construction as in (E) of Fig. 232 and is designed for battery operation in automobile or airplane receivers or in receivers operated from the d-c electric light line. The 233 type is a dry cell operated power pentode with a 2 volt type filament similar to that used in the 230, 231, and 232 type tubes. The 247 is designed for 2.5 volt a-c filament operation in electrically operated receivers.

320. Advantages of power pentode, power sensitivity: In the power pentode tube we approach the condition in which the maximum amount of plate power is controlled by a minimum amount of grid voltage fluctuation. It is a screen-grid tube adapted to power purposes for use in circuits where, with the four element tube, the grid swing would be sufficient to introduce distortion due to secondary emission.

There is a growing tendency to rate power tubes on the basis of *power sensitivity.* This is a very logical method of comparing output tubes, since their prime function is to deliver as much undistorted power to the loud speaker for a given fluctuation of grid potential as possible. At present, there exist two different definitions of this term.

Hanna, Sutherlin and Upp define power sensitivity as the ratio of watts output to the square of the R. M. S. input voltage for a given limiting percentage of distortion.

Still another definition has been proposed by Stuart Ballantine, and H. L. Cobb (proceedings of the I. R. E., March 1930). In view of the fact that sound output from the loud speaker is proportional to the square root of the power, rather than directly proportional to the power, these engineers propose that, "The power sensitivity is defined as the square root of the power output divided by the effective values of the applied sinusoidal grid voltage". By means of the latter rating we can compare directly the equivalent gains of two different types of output tubes of the same power capacity.

One great advantage of the power pentode is its great power sensitivity. For instance, the 245 type power tube which has been used as a power output tube extensively in American made receivers, consumes some 8 watts in its plate circuit, and with a 50 volt signal applied to the grid delivers 1.6 watts to the load or speaker circuit. The 247 power pentode operated at the same plate voltage of 250 volts draws a total plate and screen current of 39.5 milliamperes, so that about 10 watts are used in its plate circuit. However, the power sensitivity of this tube is so high that it will deliver 2.5 watts of undistorted power to the loud speaker when the applied signal voltage is only 16.5 volts. In other words, a single 247 pentode tube when employed in proper circuits will deliver nearly 1.5 times as much power to the loudspeaker with a signal voltage only 1/3 as much. The power pentode is about 3.3 times as sensitive as the 3-electrode power tubes commonly in use. This simply means that using a power pentode is

equivalent to using an additional amplifier stage with a voltage gain of 3.3 times. In other words, a good pentode, properly operated, will be almost as effective as two -45 tubes in push-pull, for the same power employed (in power tubes) but possessing so high an amplification constant that it definitely eliminates the first audio stage, and probably, in many instances, will function both as detector and power amplifier, with obvious added economies. The elimination of previous stages automatically eliminates the hum and incidental distortion associated with the discarded tubes.

Another application of the power pentode is in connection with phonograph amplifiers. By using a high ratio transformer to couple the pickup to the power pentode tube, sufficient power output can be obtained by using a single stage of pentode amplification working directly into the loud speaker. Another advantage of the power pentode over the 3-electrode type of power tube is the fact that with a given electrical power taken from the plate voltage supply system, the power pentode will deliver much more power to the loud speaker. This makes it especially valuable in battery operated receivers where economical battery current consumption is desirable. Its complicated structure is a disadvantage of course, as it contains so many metal parts that it is difficult to remove all the air and gas from them and it is rather difficult to make tubes of this type with uniform characteristics by ordinary quantity production methods unless strict inspection is maintained. The circuit connections of pentode tubes will be considered later in connection with battery operated and electrically operated receivers.

321. The screen-grid r-f pentode: If the extra grid of the pentode tube is kept at a positive potential with respect to the cathode, and is placed between the cathode and the control grid as shown at (F) of Fig. 232, it will neutralize partly at least, the space charge between the cathode and control grid. We will then have a screen-grid pentode whose plate current is small, whose inter-element capacity is rather high, whose power output is low and whose mutual conductance is somewhat greater than that of the ordinary form of screen-grid tube and with which greater amplification is therefore possible. Notice that the additional grid in this tube is in an altogether different place than in the power pentode, and that it serves an entirely different purpose. In the power pentode the additional grid prevents secondary emission from the plate. In this tube, which is called the *screen-grid pentode,* its purpose is merely to reduce the space charge, that is, to keep the electrons moving between the cathode and control-grid. In the screen-grid pentode, the extra grid is called the *space-charge grid* as shown at (F) of Fig. 232. It is given a positive charge by connecting it to a positive part of the "B" voltage supply device. It is unfortunate that the grid-plate capacity of the tube increases in almost the same ratio as the possible voltage gain. As a result, objectionable oscillation due to feedback from the plate to the grid circuit is likely to occur when it is used in radio frequency amplifiers, thus making some

form of neutralization or oscillation suppression necessary. In one form of screen-grid pentode constructed along the line of the popular 224 type screen-grid tube, excepting that it has the extra space-charge grid, the grid to plate capacitance is almost double that of the 224 type tube. The input capacitance between the control-grid and cathode, and that between the plate and cathode, is also about double that of the 224 tube. It is possibly this fact that will prevent this type of tube from becoming very popular for use in r-f amplifiers. The fact that secondary emission takes place in this tube, causes the entire lower part of its E_p - I_p curve to dip below the zero line indicating a reversal in direction of the plate current, somewhat as shown in the characteristic for the ordinary screen-grid tube in Fig. 228. Like the pentode, this type of tube also suffers from the fact that its structure is rather complex and it is therefore difficult to make uniformly by quantity production methods unless careful inspection is maintained.

322. Grid bias for direct heater tubes: As we shall see later, in practically all applications of the vacuum tubes as amplifiers, for best operation the control grid must be kept normally at a certain steady negative potential with respect to the electron emitter (cathode) when no signal e. m. f. is applied, the value of this steady negative potential depending on the type of tube and the plate voltage applied to it. This is called the grid or "C" bias potential or voltage. Its purpose is to set the operation of the tube at the center of the straight portion of its E_g - I_p characteristic when no signal is applied, so that when the a-c signal e. m. f. is applied to the grid circuit, it merely causes the grid potential to vary above and below this steady applied "C" bias voltage during each cycle, so the grid merely becomes more or less negative due to the signal. The grid is not allowed to swing positive, since then a grid current would flow, which is objectionable. Up to this point, we have considered that the grid was kept at some definite potential by means of a battery called the "C" or grid-bias battery, as shown at (A) of Fig. 234 when the filament is heated by a-c, and at (B) of Fig. 203 when the filament is heated with direct current by an "A" battery. The circuit may be arranged so the C bias voltage is furnished by the plate current of the tube itself, as we shall now see. In order to do this, a resistor R, (called the "C" or grid-bias resistor) is connected in the plate current return circuit as shown at (B) of Fig. 234 for the center-tapped resistor case and at (C) for the center-tapped transformer case. In either case, the operation is as follows, the same notations being used in both diagrams:

The plate current I_p flows from the positive terminal of the "B" voltage supply up through the plate circuit load to the plate, through the tube from plate to filament, down through both sides of the filament circuit and out of the center tap to point A, as shown by the arrows at both (B) and (C). From point A the current flows through the C bias resistor R from D to E, back to the negative terminal and through the B supply device, thus completing the circuit. A certain amount of the total electric potential in the plate current circuit is used up (fall of potential) in forcing this current through R. Therefore the end E of the resistor will be at a lower electric potential than the point D by an amount equal to $I_p \times R$, since in accordance with Ohm's law,

current always flows from a point of higher potential to a point of lower potential. Therefore if the grid return circuit (point F) is connected to the minus end of the grid bias resistor as shown, it will be at the same potential as point E and they are both at a lower potential than points D and A by an amount equal to the voltage drop in R. Hence if we know the plate current of a tube and the C bias voltage it requires, we can easily calculate the value of the grid-bias resistor required to produce this. The plate current and grid bias voltage required for any tube operated as an amplifier at any plate voltage may be found in the proper columns in the tube characteristic chart of Fig. 214.

Example: A 224 tube is to be operated as an amplifier with a plate voltage of 180 volts. What value of C bias resistor is required to obtain correct C bias voltage?

Solution: Referring to Fig. 214, we find that for a 224 tube operated as an amplifier with a plate voltage of 180 volts, the plate current is 4 milliamperes (.004 ampere), and the grid-bias voltage should be 3 volts. Therefore the correct value of C bias resistor to use is,

$$R = \frac{E}{I} = \frac{3}{.004} = 750 \text{ ohms. Ans.}$$

Many tubes are designed with rather thick filaments so they may be heated either with direct current or alternating current. The power tubes

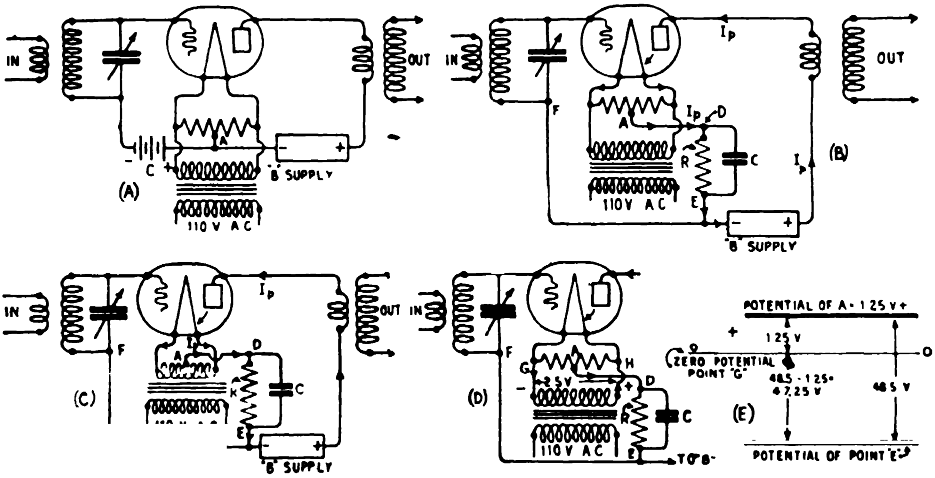


Fig 234—Methods of obtaining self-grid bias for various types of tubes.

such as the 171-A, 245, 247, etc. are of this type, although the filaments of the latter take so much current that it is usually not economical to furnish the current from batteries. However, if we look up in Fig. 214, the C bias data for the 245 tube for instance, we find that two values of grid bias voltage are specified, one for d-c on the filament and the other for a-c on the filament. The grid bias to be applied when the filament is heated with d-c is 48.5 volts negative and when the filament is heated with a-c it should be 50 volts negative, for a plate voltage of 250 volts. Similarly, the values are different for many other tubes. Let us see the reason for this.

We must remember that all differences of potential in a vacuum tube are referred to the negative end of the cathode as the point of reference. In the case of a direct-

heater type filament, this point is the *negative* end of the filament. Now in the case of a battery-operated filament, the negative end is simply the end of the side where the minus terminal of the A battery is connected. If a grid bias voltage of say 48.5 volts is specified as above, it simply means that the grid is kept at a potential 48.5 volts negative with respect to this point. However, if the filament is heated with 60 cycle alternating current instead, as shown in Fig. 234, neither end of the filament can be considered as the negative all the time, for both ends are changing alternately from positive to negative 60 times every second. Therefore we must refer our voltages to whichever end of the filament happens to be negative at the instant considered. When the left side of the filament is negative we have the condition shown at (D). Current flows out of the transformer winding and through the filament of the tube. Current also flows out of the positive terminal of the transformer winding to H, then through the center-tapped resistor to A and to G and back into the negative terminal. For the case of the 2.5 volt type of filament being considered, there is therefore a difference of potential of 2.5 volts between H and G, point H being at the higher potential. Since A is the center-tap, there will be a difference of potential of half this or 1.25 volts between point A and point G, that is, since current flows from A to G, center-tap A is 1.25 volts positive with respect to point G which is the negative end of the filament at this instant, and to which all voltages are to be referred at this instant. Therefore if the C bias resistor R was of the proper value to make point E 48.5 volts *lower* in potential than point D, since point A is 1.25 volt *higher* in potential than point G, point E is really only $48.5-1.25=47.25$ volts lower in potential than the negative end G of the filament. This may be understood better from the simple potential level diagram at (E) in which distances above the zero potential deference line O-O represent positive potentials and distances below represent negative potentials. Point A is 1.25 volts above G. Point E is 48.5 volts below A. Therefore point E is $48.5-1.25=47.25$ volts below G. These vertical distances might be considered to represent actual potential differences in volts. Now on the next half of the cycle when the right hand side of the filament becomes negative and therefore becomes the reference point for potentials, point A will again be at a higher potential than the negative end of the filament, since current now flows from G to A to N (the reader should draw the diagram for this condition), and we have the same condition.

It is evident from this, that in the case of a-c filament operation the actual voltage drop across the C bias resistor must be greater than the net effective difference of potential required between the grid and negative end of the filament at each instant, by an amount equal to half the filament voltage. In tables of tube characteristics, the actual voltage drop across the C bias resistor is called the grid-bias voltage in either case simply for convenience, although it is the true C bias voltage only in the case of d-c filament operation. This, then, is the reason for the specification of higher grid-bias voltage when a-c is used for heating the filament than when d-c is used. Taking the case of the 245 tube mentioned, we see that the difference between the specified values for a-c and d-c is $50-48.5=1.5$. This is close enough to half the value of the filament voltage of the tube ($2.5\div2=1.25$ volts). Glancing down the columns for the a-c and d-c operation, it will be seen that in each case the grid bias voltage specified when a-c filament operation is used, is equal to the value specified for the d-c filament operation plus half the filament voltage, (see Fig. 214).

Obviously, in radio equipment operated direct from the electric light circuits it is very convenient to obtain the proper grid-bias voltage for the various direct-heater filament tubes by this method, in order to eliminate the use of a battery for furnishing it. Even in battery-operated equipment, this method is very advantageous when the grid bias voltage

required is only a small percentage of the plate voltage of the tube, for it eliminates the need for frequent renewals of C batteries. Also, since the grid bias voltage furnished by the resistor R depends on the plate current flowing through it, as the B batteries get old and the voltage drops, the plate current and fall of potential through R drop correspondingly. Therefore, the grid-bias voltage applied also drops automatically so that the proper grid-bias voltage for the particular plate voltage existing is always being applied. For this reason, this system is called the *automatic* or *self-biasing* method of obtaining grid-bias voltage. We shall hereafter refer to it by the latter term.

Referring to (B) of Fig. 234 again it can be seen that the total potential difference in the plate circuit is furnished by the "B" supply device, whether this be a set of dry cell batteries, a "B" eliminator or what not. Part of this is used up in sending the plate current through the load impedance, part in sending the plate current through the plate-cathode impedance, a small part in the filament and half of the center-tapped resistor, (this may be neglected), and part in sending the plate current through the grid bias resistor R, in order to develop the grid bias voltage. If we neglect the plate-load voltage drop and the drop in the filament and center-tapped resistor, the voltage actually effective between the cathode and plate is equal to the voltage of the B supply device minus the grid bias voltage drop in the grid bias resistor. Therefore in receivers employing self bias it should be remembered that the total "B" supply voltage should be higher than the voltage actually desired on the plates, by an amount at least equal to the grid bias voltage appearing across the grid bias resistor. If the impedance of the plate circuit load is high, as in the case of a resistance coupled amplifier, there will also be considerable voltage drop in it, and this should also be considered in the above.

Since the plate current flowing through the grid-bias resistor R is varying when a varying signal voltage is applied to the grid of the tube, the fall of potential in this resistor would also vary correspondingly and therefore the grid bias potential applied to the grid would vary. Let us see just what effect this would have:

Referring to (D) of Fig. 234, let us consider the instant when the a-c signal voltage applied in the grid circuit tends to make the grid more positive (or less negative) than the applied grid bias voltage. This will cause an increase in the plate current. The increased plate current flowing through grid-bias resistor R causes an increased drop of potential in it making point E more negative with respect to the negative end of the filament than before The effect of this is to increase the negative bias voltage applied to the grid, thus tending to make the grid more negative; or looking at it another way, tending to keep the grid potential from changing as much due to the signal e. m. f. as it would ordinarily, and therefore diminishing the plate current change and volume of sound caused by the signal. This is sometimes called a *degenerative* action because it is just opposite to the signal aiding action of regeneration which we shall study later. On the next half wave, when the signal e. m. f. tends to drive the grid more negative, the plate current decreases. Instantly this results in a lower potential drop through resistor R, and a lower applied negative grid bias voltage, which tends to increase the plate current, thus opposing or weakening the effect of the signal e. m. f., in producing the plate current-changes.

The values of C bias resistors recommended for use with various types of tubes, at various plate voltages will be given in Article 324, after we have considered the arrangement to be employed for obtaining self-bias in the case of separate-heater type tubes. The degenerative effect may be decreased greatly by shunting the grid bias resistor R, with a condenser C as shown. This forms in effect a resistance-capacity filter. Let us see how this operates:

Let us assume that a steady plate current of 2 milliamperes flows through resistor R of 2,000 ohms when no signal is applied to the tube. The fall of potential across the resistor is therefore $E=I\times R=.002\times 2000=4$ volts. This charges the plates of condenser C connected across it to a difference of potential of 4 volts. Now the first half of the first alternation of the a-c acts on the grid, drives the grid potential more positive. The plate current increases, and therefore more electrons tend to pass through R every second. Since R offers a resistance of 2,000 ohms to the flow of electrons through it, if condenser C is of large enough capacitance, so that it offers a substantially lower reactance to the flow of electrons into it at this frequency than resistor R does, these additional electrons will accumulate into its negative plate instead of going through the resistor. Therefore the resistor still carries practically the same current as before and so the voltage drop across it is the same and the grid bias voltage has not been affected. It is assumed that condenser C is of large enough capacitance so that these additional electrons crowding into its negative plate during this small interval of time do not increase the potential difference between its plates to any noticeable extent. Now the next part of the signal impulse comes along and drives the grid potential more negative. This tends to reduce the plate current, i.e., reduce the number of electrons drifting through resistor R. The condenser being charged to maximum potential during the previous increasing plate current impulse, will now discharge part of the excess electrons from its negative plate. These go through the resistor and therefore help to keep the voltage drop across it steady. The same thing is repeated over and over on each signal impulse, the condenser storing electrons when the plate current increases and releasing them when the plate current decreases, so that the grid bias voltage obtained from resistor R remains substantially constant. It is assumed that the condenser is of large enough capacitance so that its reactance to the flow of electrons (current) at the frequency encountered in the circuit is much lower than the resistance R which it is shunting. Of course the larger the condenser capacitance is, the better, but the element of condenser cost and space available limit the size of by-pass condensers which can be employed in practice. For practical purposes, in radio-frequency circuits a by-pass condenser is chosen of such a capacitance that its reactance at the frequency of the signal e. m. f. and plate current impulses is less than from one-one hundredth to one-one thousandth that of the resistor it is shunting. In audio-frequency circuits, the condenser reactance is usually kept down to about 0.1 the value of the resistance it is shunting. It has become common practice to use by-pass condensers of 0.2 to 0.5 mfd. for shunting grid bias resistors of r-f amplifier tubes used in broadcast receivers where the frequency may be anywhere from 500,000 to 1,500,000 cycles per second; and to use by-pass condensers from 1 mfd. to 4 mfd. for shunting those used in audio-frequency amplifier circuits where the frequency of the signal e. m. f. and plate current pulsations varies from below 100 cycles to above four or five thousand cycles per second.

The size of condenser to use is determined by the lowest frequency encountered, for since condenser reactance decreases as the frequency is increased, a by-pass condenser good for the lower frequencies will be even better for all frequencies higher than this. The table of condenser reactances in Article 166, may be used for quickly finding the reactance of any size of condenser at almost any frequency. Condensers of the non-inductive type (see Articles 141 and 142) should be employed for this service. By-pass condensers used for this purpose are usually of the paper dielectric or mica dielectric type as shown in Figs. 90 and 91.

Problem: What is the capacitance of a by-pass condenser which will have one-one-thousandth the reactance of the 2000 ohm non-inductive grid-bias resistor it is shunting, at a frequency of 500,000 cycles per second when used in the circuit of an r-f amplifier tube?

Solution: The resistance offered by the resistor is 2,000 ohms regardless of the frequency, provided it is non-inductive. Therefore the reactance of the condenser must be equal to $\frac{2000}{1000}=2$ ohms. Referring to the table of condenser

reactances in Article 166, we find that the capacitance required which has a reactance of 2 ohms at 500,000 cycles may be a 0.25 mfd. condenser. This will have a reactance of 1.28 ohms at this frequency. A 0.2 mfd. condenser will also do, since its reactance would be 1.6 ohms.

Problem: A 227 tube in an audio amplifier in which the lowest frequency is 120 cycles per second, employs a 2,000 ohm grid-bias resistor. What must be the capacitance of the by-pass condenser to be used across it if the condenser reactance is to be not more than about one tenth the reactance of the resistor at this frequency?

Solution: $2000 \div 10 = 200$. Referring to the condenser reactance table in Article 166, we find that at 120 cycles per second, a 6 mfd. condenser has a reactance of 221 ohms. This condenser will therefore be suitable for the purpose. Ans.

The use of a bias resistor in the cathode lead to derive a voltage from the plate current drop, leads to several complications in the case of the power pentode. Since the amplification factor is high, the degenerative effect of audio voltage across this bias resistor is marked in effect. To eliminate this effect which results in decreased power output and loss of fidelity, it is usual to bypass the resistor to B— with a condenser, as we have just seen. The value of capacity necessary with the '47 type pentode is prohibitively large. To reach an optimum for reproduction down to 60 cycles the capacitance would have to be about 10 microfarads since the C bias resistor would have to be about 418 ohms (actually about 400 ohms is used for the grid bias resistor). Of course an electrolytic condenser can be used for by-passing, but there are other better ways of obtaining the grid-bias. Fixed bias by means of a "bleeder" resistor from some point in the "B" supply can usually be obtained by the drop across a resistor of much lower value and can be de-coupled easily from the grid and plate circuits of the pentode as we shall see later when studying receiver circuits in which power pentode tubes are employed. The method of obtaining grid-bias from some point in the B power supply unit is also used extensively for tubes other than pentodes.

323. Grid-bias for separate-heater tubes: Grid-bias for separate-heater type tubes can also be obtained by connecting a grid-bias resistor in the plate return circuit of the tube. It is most conveniently connected as shown at (A) of Fig. 235. The plate current flows from the plate to the cathode, through the grid bias resistor to the negative terminal of the B voltage supply as shown by the arrows.

Since the plate current flows from D to E, point D is at a higher potential than point E, i.e., E is negative with respect to D by an amount equal to the voltage drop $E = I \times R$ in the resistor R. If the grid return wire from F is connected to the lower end E of the grid-bias resistor as shown, both it and the grid will be kept at this negative potential with respect to point D and the cathode. As explained in Article 322, a by-pass condenser C must be connected across the resistor, its value depending on the resistance of R and the lowest frequency of the pulsations of the plate current which is to flow through the resistor. This value depends of course on whether the tube is to be used in a radio frequency circuit or an audio frequency circuit. In the case of a screen-grid tube or variable-mu tube, the

same circuit connections may be employed as shown at (B), excepting that since both the plate current and the screen grid current flow back through resistor R, the sum of the two should be used as the current when calculating the value of the grid-bias resistor required, by Ohm's law.

324. Grid-bias for several tubes: In the interests of economy, in radio receivers employing several tubes of the same type, and operated at the same voltages, since similar grid-bias voltages are required they may all be obtained from a single resistance. In the case of direct-heater type tubes, the grid-bias resistor is connected in the center-tap lead of the single

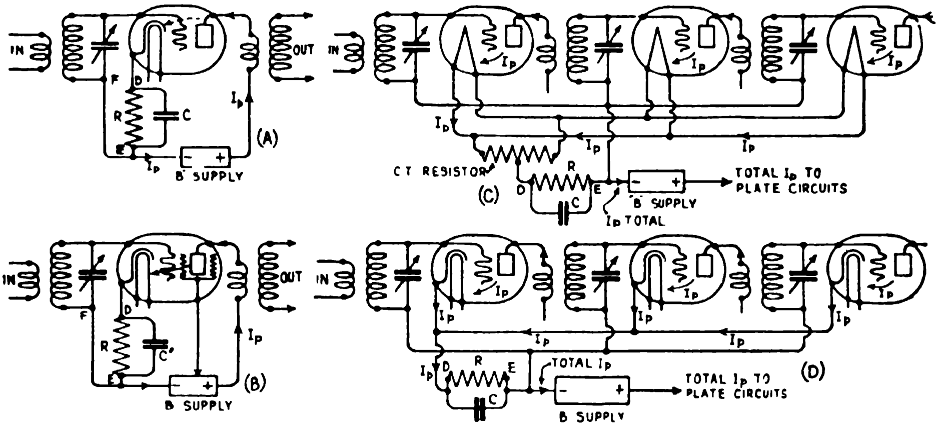


Fig 235—Obtaining negative grid-bias voltage for separate-heater type tubes.

center-tap resistor (or center-tap on the transformer winding) as shown at (C). Since the combined plate currents of all the tubes flow through this resistor, its value in Ohms should be less than that used for a single tube. Thus, if two tubes are operated from the same grid-bias resistor, since twice as much plate current flows through the resistor as for a single tube, it should be of only half the resistance value for the same bias voltage drop. For three tubes it is 1/3 as large as for 1 tube, etc. This may be understood from the following problem:

Problem: From Fig. 214 it is found that at a plate voltage of 250 volts applied through a plate coupling resistor of 200,000 ohms, the plate current of a 224 screen-grid tube operated as an audio amplifier is .5 milliamperes (.0005 amps.) and the grid bias is 1.0 volt negative. Calculate the grid bias resistor required for (a) a single tube, (b) two tubes operating with one resistor, (c) five tubes operating with one resistor.

Solution: (a) $R = \frac{E}{I} = \frac{1}{.0005} = 2000$ ohms.

(b) with two tubes, double the plate current flows through the resistor.

Therefore: $R = \frac{1}{.001} = 1000$ ohms (half as much as for 1 tube).

(c) for five tubes $R = 2000 \div 5 = 400$ ohms. Ans.

In the case of several separate-heater type tubes obtaining their grid-bias voltage from a single resistor, the connection is as shown at (D), all the cathodes are connected together. The resistor is connected in the combined cathode return lead so that the total plate current of all the tubes flows through it. The value of the resistor is calculated in the same way as for the cases explained above. Of course these connections for the grid-bias resistor are the same for either 3-electrode type tubes or screen-grid tubes, and for either radio-frequency or audio-frequency amplifier circuits. Similarly, when two vacuum tubes are connected in parallel or push-pull, the plate current through the common grid-bias resistor is double that of a single tube, and therefore in order to obtain the same fall of potential for use as grid-bias, only half the value of resistance should be employed as would be used for a single tube.

The following table furnishes the values of R to be used for proper grid-bias for various commonly used tubes when their filaments are operated with a-c. The grid-bias resistor values given are for a single tube, and are calculated from the grid-bias voltage and plate-current values given in Fig. 214. The nearest resistor value which is easily obtainable commercially has been specified in each case, since a few ohms difference in the value of the grid-bias resistor will not affect the operation of the tube.

TABLE OF GRID-BIAS RESISTOR VALUES

Type of Tube	Grid Bias Resistor For A Single Tube (Ohms)					
	90 V. Plate	135 V. Plate	180 V. Plate	250 V. Plate	425 V. Plate	450 V. Plate
226	1600	1400	1800	..	..	..
227	2200	2000	2700			..
224	.. ..	..	375 with	75 V. on	Screen	2000
224	.	..	750 with	90 V. on	Screen	....
171A	1600	1700	2200		...	....
245	.....	1400	1500		....	...
247	....	....		420		.
210	....	..		2200	2200	
250	......			1600	1550	1500

Note: The resistance values given above are for a single tube. If two tubes are to be operated from the same grid bias resistor, only half this resistance value is required, etc.

Later, when studying B power supply devices and modern a-c electric receivers, we will see how grid-bias voltages are obtained in many such receivers by making use of voltage drops occurring in loud speaker field windings, bleeder resistors, etc. The latter methods are used in many radio receivers on account of their convenience, low cost, and several advantageous operating features, which will be explained.

325. Vacuum tube construction: Vacuum tubes are made in many forms, with various sizes, shapes and arrangements of electrodes in order to produce certain desirable characteristics to make the tube best suited for a particular use. The filaments may be designed to be operated from dry cells, storage batteries or raw alternating current. The tubes can be constructed to handle from a few milliwatts to several thousand watts of power. The filaments may be either of the thoriated tungsten type or coated with the oxides of barium or strontium to increase the electron emission for a given temperature. They may be made in the form of round wires, or flat ribbons; arranged in the form of a straight wire, an inverted V, a double V, etc. The plates are usually plain box-shaped, or cylindrical, with the grids corresponding. The relative spacing of grid, filament, and plate, as well as the fineness of the mesh in the grid, also varies in the different tubes. Some tubes have been designed with a multiplicity of filaments, grids and plates. In Europe, some tubes have been designed with multiple elements so as to contain within the glass bulb all the necessary parts for one or two amplifier stages. These have not attained great popularity in the United States.

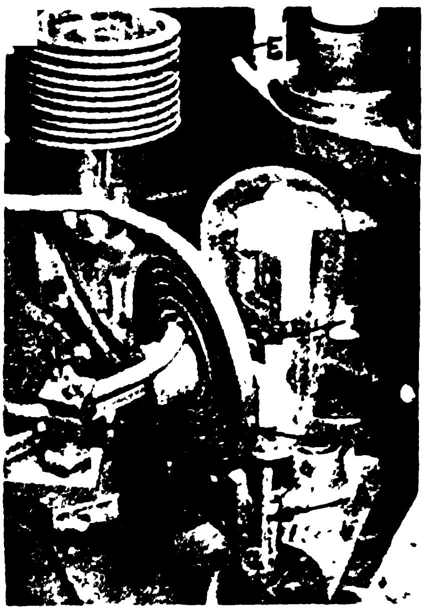
Illustrations of several types of vacuum tubes are shown in Figs. 193, 196, 215, 220, 226, 227, 229 and 233. The student should study these carefully at this point. The construction of the filament has already been considered in Articles 299 and 301. We have seen that the oxide coated type is the most popular at the present time. The usual recommended limits of filament voltage variation are plus or minus five per cent of rated voltage. This means that the maximum permissible voltage is equal to 1.05 times the rated voltage and the minimum permissible voltage is 0.95 times the rated voltage. For a 227 tube rated at 2.5 volts these values are found to be 2.63 and 2.38 respectively. This overall range of ten per cent takes care of slight line voltage variations which may occur in receivers operated from the electric light lines, but is, of course, not sufficient to take care of any wide variations in line voltage, for in some localities (small towns especially), the line voltage may vary as much as twenty-five per cent.

The grids are usually made of fine molybdenum ("molly"), or nickel wire, wound in the form of either a round or flattened spiral, around two nickel supports, and welded, or otherwise fastened to them, at each turn. The inner screen-grid in the '24 type of screen-grid tube consists of a nickel wire. The outer screen grid is of nickel mesh as shown in Fig. 227. The chief advantages of mesh as an outer element material for radio tubes are that it permits free radiation of heat from the intermediate elements, whose operation at low temperatures is desirable, and that during the evacuation process it permits more rapid inductive heating of the elements which it surrounds. The former advantage is of great importance in tubes where a considerable amount of heat is given out by the filament. The advantages of nickel as a mesh material are many: it is pliable, and the mesh can be readily formed into any shape desired; it is easily cleaned by baking in a hydrogen atmosphere, and is relatively immune to tarnishing on standing or handling; it can be readily spot-welded to other nickel parts; it has a relatively high melting point; and it can be secured in a pure state and at a reasonable cost. The use of nickel mesh is restricted to the outer element of the tube for several reasons. The two grids within the plate of a screen-grid type tube are of comparatively small diameter, must be accurate in diameter, and if made of mesh would have to be of very open weave. Under these conditions, a more satisfactory grid can be manufactured using a spirally-wound wire than using woven mesh. In order to obtain satisfactory operation, the plate of the tube would have to be of very fine woven material if mesh were used; because of the difficulty and cost of weaving such fine mesh, solid nickel strip is still used for the plate by many manufacturers.

The greatest obstacle encountered in the production of good vacuum tubes is gas. Utmost precautions must be taken to be sure that all the gas is removed from the tube before sealing. For this reason the pumping is carried out as far as possible within the economic time limit, followed by the flashing of a chemical or "getter" to clean up the

remaining gases. The metal parts are frequently baked in a hydrogen atmosphere, to remove the oxygen from the pores of the metal. Even so, with nickel for the support wires, plate and grid, there is considerable imbedded gas which is certain to be liberated when the tube is in use, resulting in gassy tubes. For this reason, molybdenum or "molly" plates are frequently used, also molly wire is used for supports and grids. However, this metal is far more expensive than nickel, and introduces a serious increase in cost. This is a very important consideration in a field such as the vacuum tube industry, which is highly competitive. For this reason, the nickel parts continue in general use. The plates of power tubes, rectifier tubes, and other large tubes are covered with a carbonized surface layer. This makes them rough and black and aids in increasing the radiation of heat from them. The filament is supported at the bottom and top. In some tubes, additional bracing to prevent mechanical vibration of the elements is secured by a piece of mica holding the grid, filament and plate supports rigidly at the top. This reduces microphonic noises caused by variation of distance between the elements due to mechanical vibration. The slight variation of element spacing due to vibration would cause the plate current to vary likewise, resulting in a sound of the same vibration frequency from the loud speaker.

326. Manufacture of vacuum tubes: Fig. 196 shows the assembly stages of a 201-A type vacuum tube. Fig. 227 shows a few of the assembly stages of a 224 type screen-grid tube. The metal parts are first assembled on the metal supports and fastened mostly by spot-welding. The entire assembly is mounted on a glass flare through which the connecting wires are sealed, and from which a hollow tube extends at the bottom. The flare is then sealed to the outer glass bulb as shown at the right of Fig. 196, making an upright assembly.



Courtesy Electronics Magazine

Fig 235A—"Bombarding" the metal parts of a vacuum tube during evacuation The air being pumped out of bulb C through glass stem A B is the "bombarder" coil which flashes the "getter" at D E is the "bombarder" coil which heats up all the metal parts to release the air trapped in the pores of the metal and glass

The long glass tube is attached to the special high vacuum pumps which exhaust the air out. Several tubes are placed on a manifold for exhaust. They are heated by gas flames while the exhaust pumps are in operation. This quickly drives out all air and gas bubbles which may be entrapped in the pores of the walls of the bulb and all of the metal and glass parts inside of it. For a similar reason, the filament is usually kept heated by an electric current during this time. The elements are now heated to a red heat to drive out any remaining gas, by means of an external radio-frequency induction coil called a "bombarder" which drops over the glass bulb as shown at E of Fig 235A. The rapidly alternating powerful magnetic field of the coil induces powerful eddy currents in the metal parts inside, which heat them to a red heat and thereby helps to free the occluded gases which are immediately drawn off by the pumps. Of course the field has no effect on the glass bulb which is an insulator. After the tube has been evacuated as much as possible by the pumping process, it is sealed off, and the high frequency bombarder coil which is lowered over the tube heats the elements excessively to a red heat by induction. This forces out the remaining gas molecules since they expand due to the heat, and at the same time the "getter" material vaporizes and enters into vigorous chemical combination

with the freed gases. Upon removal of the high-frequency coil, the vaporized "getter" condenses on the comparatively cool inner walls of the tube where it forms the familiar silver or reddish film so noticeable in vacuum tubes.

Several materials are suitable for use as getters. Among the more common are: magnesium, (same as ordinary flashlight powder), barium, aluminum, Misch-metal (a mixture composed of several rare metals of the cerium-group), calcium and cerium. Magnesium and barium are perhaps the two most widely used getters. A tiny metal cup containing the getter is usually mounted in an inverted position, usually below and to the side of the plate, so the getter is not thrown against the metal elements in the tube when it vaporizes. All of the operations of sealing the flare to the bulb, evacuating, bombarding, flashing and sealing-off are performed automatically by modern machinery. A number of tubes are mounted on a large circular turntable, which rotates slowly. Each tube comes around in succession to the devices which automatically perform the various operations described above. It is due to automatic machinery of this type that the cost of manufacture of vacuum tubes has been decreased so markedly during the past few years.

After the tube has been sealed off, it is cemented to the Bakelite base and the lead-in wires are solderd to the tube prongs. These are made of hollow brass tubing, plated to prevent further corrosion. The tube is then tested and aged by operating it at definite filament voltages for certain lengths of time until the filament emission becomes stable and constant. A rough test for gas content is made by bringing a high-frequency spark coil up near to the glass bulb. If the tube contains an excess of gas, it will be ionized by the rapidly alternating field of the coil and the characteristic blue glow due to this ionization will be produced.

The actual measurement in finished vacuum tubes consists in measuring the "inverse" current that flows in the grid circuit under some standard condition of operation of the radio tube. By "inverse" current is meant a current which flows in the grid circuit when the grid is negative with respect to the filament, that is, a current which flows in the sense of grid to filament in the exterior circuit. It can be demonstrated that this current originates from the ionization of the gas tube, and is therefore largely proportional to the gas content of the tube.

In the common types of radio tubes, the magnitude of the grid current is from a few hundredths of a microampere to several microamperes, depending on the excellence of the vacuum in the tube and the test conditions chosen. Currents of this size represent about the lower limit of sensitivity of the very best portable electrical measuring instruments that can conveniently be used in factories and factory laboratories.

Every possible effort is made to not only produce as perfect a vacuum as possible in modern vacuum tubes, but by means of the heating of the metal parts and the flashing of the "getter", to eliminate even the small bubbles of gas and water vapor absorbed in the microscopic pores of the metal and glass parts. The exhausting apparatus consists of mercury vapor pumps in series with ordinary rotary or reciprocating pumps. Gas pressure is usually measured by the height of the column of mercury it will support. A *micron* of pressure is equal to that exerted by 1/1000 of a millimeter of mercury. The average new vacuum tube has a vacuum of 2 or 3 microns, a micron being one-millionth of the usual atmospheric pressure of 15 pounds per sq. in. An incandescent lamp has a vacuum of 150 microns. Special long-life tubes are being made with a vacuum of less than 1 micron.

A "soft" or low-vacuum tube cannot withstand the high voltages necessary for amplification, although it may be used at low voltages as a detector. The life of a tube is largely dependent upon the degree of vacuum existing in it, varying from 100 hours for a poor vacuum to several thousand hours for a good vacuum.

The structure of vacuum tubes calls for the use of various metals, and other materials. An idea of the many materials entering into the actual construction and manufacturing processes connected with the manufacture of various types of vacuum tubes, may be obtained from the following list which is published here by the courtesy of the R. C. A. Radiotron Co.

GLASS BULBS AND PARTS

Silver oxide
Lead acetate
Glycerine
Silica
Sodium carbonate
Calcium oxide
Sodium nitrate
Lead oxide
Borax
Zinc oxide
Cobalt oxide
Potassium carbonate
Calcium aluminum floride
Arsenic trioxide

BASES

Isolantite
Bakelite
Porcelain
Wood fiber
Zinc
Copper
Nickel
Tin
Marble flour
Ethyl alcohol
Nigrosine
Zinc Chloride
Malachite green
Ammonium chloride
Petroleum Jelly

SUPPORTS

Glass
Mica
Lava
Magnesia
Nickel
Molybdenum
Monel
Alumina

LEADS

Iron
Nickel
Copper
Zinc
Borax

GETTERS

Magnesium
Calcium
Strontium
Barium
Caesium
Phosphorus
Carbon
Mercury
Mischmetal

ELECTRON EMITTERS (filaments and cathodes)

Tungsten
Thorium nitrate
Carbon
Nickel
Platinum
Iridium
Cobalt
Iron
Titanium
Silicon
Barium carbonate
Strontium carbonate
Calcium carbonate
Barium nitrate
Strontium nitrate
Silica
Alumina
Magnesia

PLATES

Nickel
Monel
Molybdenum
Iron

GRIDS

Nickel
Monel
Copper
Molybdenum
Chromium

GASES USED IN MANUFACTURE

Hydrogen
Helium
Neon
Argon
Nitrogen
Oxygen
Natural Gas

Copper and iron find their way into the manufacture of tubes in the form of stem leads. A special heavy iron wire is wrapped with copper and drawn down through dies until their combined diameter is the proper size desired. Thus a small iron wire with a thin shell of copper is formed, known as "copper-clad." Copper-clad possesses practically the same expansion and contraction as glass and can be fused into glass without fear of cracks due to unequal expansion, hence the tube will not lose its vacuum because of cracks which might otherwise be formed.

327. Effect of gas in a vacuum tube: The foregoing explanations of the actions taking place in the vacuum tube were based on the supposition that a very perfect vacuum existed in the tube. Under these conditions, the tube operates entirely by the normal unimpeded electron stream between the filament and plate. If the space in the tube contains more than the slightest trace of gas, and the plate voltage is high, the operation is somewhat more complicated, and a larger plate current will usually flow for a given plate voltage, provided ionization takes place.

The actual rate of emission from the filament is not affected, but the liberated electrons on their way to the plate collide with the atoms of the gas, causing "ionization by collision". On account of this action, larger plate currents will usually flow with a given plate voltage in tubes having a poor vacuum. Air of course is a gas. Present day vacuum tubes are made with a high degree of vaeuum so that no ionization takes place.

Ionization in a tube might at first seem desirable, since its effect is to increase the plate current. Actually, however, it is undesirable since it interferes with the

normal operation of the tube. Also, since the ions which are driven violently against the negatively charged filament are much more massive than electrons, the bombardment actually seems to tear away the surface of the filament, disintegrating it and reducing its useful life. Ionization in a tube is usually accompanied by a visible blue glow discharge, although a blue glow in a tube may be produced by other actions which are not harmful. The tube usually becomes very erratic in behavior when in this condition. It is not sensitive in a receiver, since the plate current becomes so large due to the ionization that it is practically unaffected by variation of the grid voltage. Some of the old gas-filled detector tubes could be made to ionize strongly at plate voltages as low as 100 volts. Tubes containing some gas are called *soft* or *gassy* tubes. They were very popular one time for use as detectors. Tubes having a very high degree of vacuum are called "hard" tubes. They make the best amplifiers.

Practically all tubes used in modern radio receivers are high-vacuum or "hard" tubes. Tube manufacturers employ elaborate machinery and manufacturing operations in a special effort to remove every last trace of air from the inside of the tube during the course of manufacture. The scientific "de-gassifying" processes applied to remove even the slight amount of air entrapped in the pores of the metal elements and inside surface of the glass tube are well known examples of this. This is partly due to the effort to produce tubes having longer filament life, and to the practical problem of producing tubes for operation at high plate voltages. These high plate voltages (such as exist in the 245, 210 and 250 type tubes) cause ionization effects which would be absent in tubes designed for lower plate voltages, for a given amount of air or gas present. Commercial forms of "gassy" tubes are apt to be rather non-uniform on account of the practical difficulties involved in manufacturing tubes of this type on a large scale by quantity production methods, and turning out a high percentage of perfect tubes which are all exact duplicates of each other, each having the same number of molecules of gas.

REVIEW QUESTIONS

1. Why are many different types of vacuum tubes manufactured? Would it not be better to have a single standard type of tube?
2. What is the purpose of the filament in (a) the direct-heater type of tube; (b) the indirect-heater type of tube?
3. Describe the two types of filaments used in the former types of tubes, and explain the advantages of each. Which one is used most?
4. What causes a decrease of electron emission in the thoriated tungsten filament and how can such a filament be reactivated? Is this possible with an oxide-coated filament?
5. What materials are used for (a) oxide-coated filaments; (b) oxide-coated cathodes?
6. How should a tube be tested for "emission"?
7. Explain two causes of the hum produced if an ordinary thin filament such as is used in the 201-A type of tube, is heated with alternating current.
8. What special construction features do the filaments of direct-heater type tubes suitable for a-c filament heating have?
9. How is hum-free operation obtained in the separate-heater type of tube? Draw a sketch showing the construction and relative location of the elements of a 3-electrode tube of this type. Mark on it, the complete filament and plate circuits.
10. What is the purpose of the center-tapped resistor, or center tapped filament transformer winding, used when a-c filament

operation is employed? State which method is best,—with your reasons. Where should the C-T resistor be placed in the set?

11. State several advantages of separate-heater type tubes over the 226 type tubes, for a-c filament operation. Why may direct-heater type tubes be employed in the last audio stage of a receiver, without resulting in objectionable hum?
12. What supplies the low a-c filament voltages required for a-c tubes?
13. What happens to a tube when the oxide-coating on the cathode has all been used up? What must be done when a tube reaches this condition?
14. Draw a simple circuit diagram showing a filament heating transformer supplying a-c current to the filaments of five separate-heater type tubes if (a) the filaments are connected in parallel, (b) if the filaments are connected in series. What are the advantages of each arrangement?
15. Why must the filament circuit connecting wires in a-c operated receivers be run close together or twisted?
16. The filaments of four type 235 tubes, two type 227 and two type 247 tubes in a radio receiver are all connected in parallel. Assuming that each filament is rated at 2.5 volts and 1.75 amperes, calculate the total current and voltage which the low-voltage filament winding of the transformer must supply to the tubes. What is the total wattage supplied to all the filaments? If the efficiency of the transformer is 80 per cent, how many watts are taken by its primary from the 110 volt a-c line?
17. Draw a sketch showing the capacitances which exist between the various elements in a 3-electrode vacuum tube, marking each one with its proper name.
18. Explain (with sketches) how feedback can take place from the plate circuit to the grid circuit of an r-f amplifier stage, due to large grid-to-plate capacitance in the tube. Why is oscillation in an r-f amplifier objectionable?
19. Explain (with sketches) the construction of the 4-electrode screen-grid tube and show how this construction greatly reduces the grid-plate capacitance of the tube.
20. What is the approximate capacitance between the plate and grid in a 227 type tube, and to what value has it been reduced in the 224 screen-grid type?
21. Explain (with sketches) (a) the cause of space-charge in a tube; (b) why it is objectionable; (c) how the arrangement of the elements in a space-charge grid tube greatly reduce it. Why is the space-charge grid form of tube not used for radio-frequency amplification?
22. What is a variable-mu tube? Explain the special feature of its construction (with sketches) which is responsible for its par-

ticular characteristics. Also explain what happens as the potential of the grid is made more and more negative. In what part of a radio receiver is this type of tube used especially. Why?

23. What is the difference between the purpose of an ordinary amplifier tube and the purpose of a "power tube"? What is meant by the "power sensitivity" of a power tube?
24. Explain (with sketches) the construction and arrangements of the elements (a) in the power pentode tube, (b) in the screen-grid pentode tube. What causes secondary emission in a tube; what harmful effects does it have on the operation of the tube; and how is it prevented in the pentode?
25. What are the advantages of the power pentode over the ordinary 3-electrode forms of power tubes? What important disadvantage does the screen-grid pentode have, that reduces its desirability as an r-f amplifier tube?
26. Draw simple sketches showing the relative location of the electrodes in the following types of tubes: (a) 3-electrode; (b) screen-grid; (c) variable-mu; (d) space-charge grid tube; (e) power pentode; (f) screen-grid pentode. Assume separate-heater construction in each case and mark the names of the elements on each sketch. Now starting with the 3-electrode tube, point out briefly the difference in the construction between each type and the particular special characteristics which this results in.
27. Draw a practical circuit for obtaining proper grid bias for two 227 type tubes operated as r-f amplifiers in a broadcast receiver, with a plate voltage of 180 volts. From the grid-bias voltage and plate current values given in the table of Fig. 214, calculate the value of the grid-bias resistor required to obtain correct grid bias voltage. What size of by-pass condenser would you employ across the resistor?
28. Repeat question 27, using three 224 type tubes operated with a plate voltage of 180 volts and a screen voltage of 75 volts. Explain in detail, how the grid-bias voltage is obtained in each case.
29. What value of resistor would be used in each case if only a single tube were used?
30. What are the grid and plate in a vacuum tube usually made of? Why?
31. Explain briefly the process of manufacture of a vacuum tube, including in your discussion the reason for the use of the "bombarder", and the "getter".
32. Why is it so necessary to eliminate every possible trace of air from a tube, even to the extent of liberating the tiny air bubbles which are entrapped in the pores of the metal parts and glass bulb?

CHAPTER 20

VACUUM TUBE DETECTOR AND AMPLIFIER ACTION

THE VACUUM TUBE DETECTOR — GRID BIAS DETECTOR — GRID LEAK AND CONDENSER DETECTION — SQUARE LAW AND LINEAR DETECTORS — POWER DETECTION — GRID LEAK AND CONDENSER POWER DETECTION — GRID BIAS POWER DETECTION — TWO-ELECTRODE LINEAR POWER DETECTOR — COMPARISONS OF DETECTOR ARRANGEMENTS — VACUUM TUBE AMPLIFIER ACTION — MAXIMUM VOLTAGE AMPLIFICATION — CONDITIONS FOR UNDISTORTED AMPLIFICATION — DISTORTION DUE TO INCORRECT GRID BIAS — DISTORTION DUE TO OVERLOADING — DISTORTION DUE TO CURVED CHARACTERISTIC — RESULTS OF TUBE DISTORTION — TESTING FOR DISTORTION — REVIEW QUESTIONS.

328. The vacuum tube detector: In Chapter 16, the manner in which electromagnetic radiations from radio transmitting stations are intercepted by the receiving antenna and the way in which the principle of electrical resonance (tuning) may be employed to allow only the signals of that station which it is desired to receive, to pass through the receiver was explained. The necessity for some form of detector arrangement which not only changes the alternating high-frequency signal voltages into pulsating direct current, but also makes the earphones or loudspeaker responsive only to the successive maximum values or envelope of the rectified r-f current was also explained. We found that this could be accomplished by means of the simple crystal rectifier or detector with a small condenser connected across the speaker, but that crystal detectors are no longer used to any extent in radio receivers because of several objectionable features which they have. The reader should review Articles 252 and 254 briefly at this point. The function of the so-called "detector" in radio receivers is really that of *demodulation*. We learned that in the transmitting station, the audio-frequency voice-currents are made to modulate the strength of the successive cycles of the high-frequency carrier current as shown at D of Fig. 171 and in Fig. 172-A. The function of the detector in the receiving circuit is just the reverse of this. It must "de-modulate" or separate the radio-frequency current cycles from the audio or voice frequency variations as shown in Fig. 186. The term "de-modulation" is really more descriptive of the real action of this device than "detector" is. We shall often refer to it as such in our work. It should always be remembered that the detector does much more than merely rectify the a-c signal impulses to d-c plate current. It must also remove the r-f variations in the plate current. In this, it is assisted by the plate circuit capacitance, as we shall see. The vacuum tube can be made to act as a detector or demodu-

lator by connecting it in either of two ways. One is by keeping the grid excessively negative by a grid-bias voltage, so the tube operates at the lower bend of its characteristic curve. This is known by the various names of *C-bias* detection, *grid-bias* detection and *plate-current* rectification. The other is by means of a grid condenser and resistor connected in the grid circuit. This is called *grid leak and condenser* detection, or *grid circuit* rectification. The former method is used most in our present day powerful receivers and will be explained first.

329. Grid bias detector: During our study of the characteristic curves of vacuum tubes, we found that two bends occur in the usual E_g - I_p curve, one at the bottom and one at the top as shown at (D) in Fig. 236. The lower bend E, occurs at some negative grid potential value and the upper bend F, occurs at some positive grid potential value. If the proper value of negative grid bias voltage is applied to the tube by means of a C battery in the case of a battery-operated tube as shown at (A), or by a grid-bias resistor in the case of a separate-heater type a-c tube as shown at (B) for a 3-electrode tube and at (C) for a screen-grid tube, the tube may be made to operate at the bend of the curve. This is the condition under which grid-bias detection can be accomplished. A detailed explanation of the action which takes place follows:

Let us suppose that a negative grid bias potential has been applied to the grid circuit, so that in the absence of a radio signal voltage, the grid assumes a steady voltage which is the same as the potential of the grid-return lead. The *grid-return lead* is the wire which completes the circuit from the lower end of the tuned circuit back to the negative terminal of the C-bias voltage source, see (B). This actual grid voltage is the *operating grid potential*, and gives the point E on the E_g - I_p characteristic of (D) of Fig. 236 at which the detector tube operates. Under this condition a steady plate current I_p flows, whose value is represented by the height of point E above the zero plate current axis.

When a radio-frequency signal voltage such as is developed across the tuning coil and condenser LC at (A) is applied to the detector grid, this voltage is superimposed upon the steady operating grid potential, making the actual grid potential alternately more and less than the operating grid potential. This is illustrated at (D) where the curve representing the signal voltage applied to the grid is drawn vertically below, about the normal operating grid potential as an axis. This voltage curve starting at 1, increases to 2 in the negative direction, then back to zero at 3, then to 4 in the positive direction, and so on for a number of cycles. The "plate current" curve shows the corresponding changes produced in the plate current, decreasing from 1 to 2, increasing from 2 to 4, etc. For any point on the signal voltage curve, there is a corresponding point marked with a similar number in the plate current curve. Take any point on the signal voltage curve, such as point 2. Draw a line up from 2 to the characteristic curve as shown by the dotted line in the figure. From the point of intersection, draw a horizontal dotted line to the right. This determines corresponding point 2 on the plate current curve. By repeating this construction for a number of points, the plate current curve is determined, the horizontal scale of this curve being the same as that for the grid voltage curve.

Let us examine the plate current curve to see what has happened. First, we see that for each cycle of the a-c signal voltage the plate current decreases a small amount, as from 1 to 2 to 3, but also increases a larger amount from 3 to 4 and back. That is, due to the bend in the E_g - I_p curve, the plate current changes produced by equal half cycles of the signal voltage in opposite directions, are not equal. Therefore, the plate current variations are not symmetrical. It is evident that the sharper the bend of the E_g - I_p curve is, and the nearer the operating grid potential is set to the value corresponding to the exact bend, the more perfect will be the cut-off of the plate current changes caused by the negative half cycles of the signal voltage, that is, the more

perfect the rectification. It will also be noticed that the plate current variations as represented by the portion of the plate current curve above the dotted line is practically a duplicate as regards wave-form, of the signal voltage variations. Furthermore the changes in grid voltage due to the signal have been *amplified* by the tube. This is one important advantage of the vacuum tube detector over the crystal detector since the former not only performs the process of demodulation, but also amplifies the signal voltage changes, whereas the latter acts merely as a rectifier and produces no

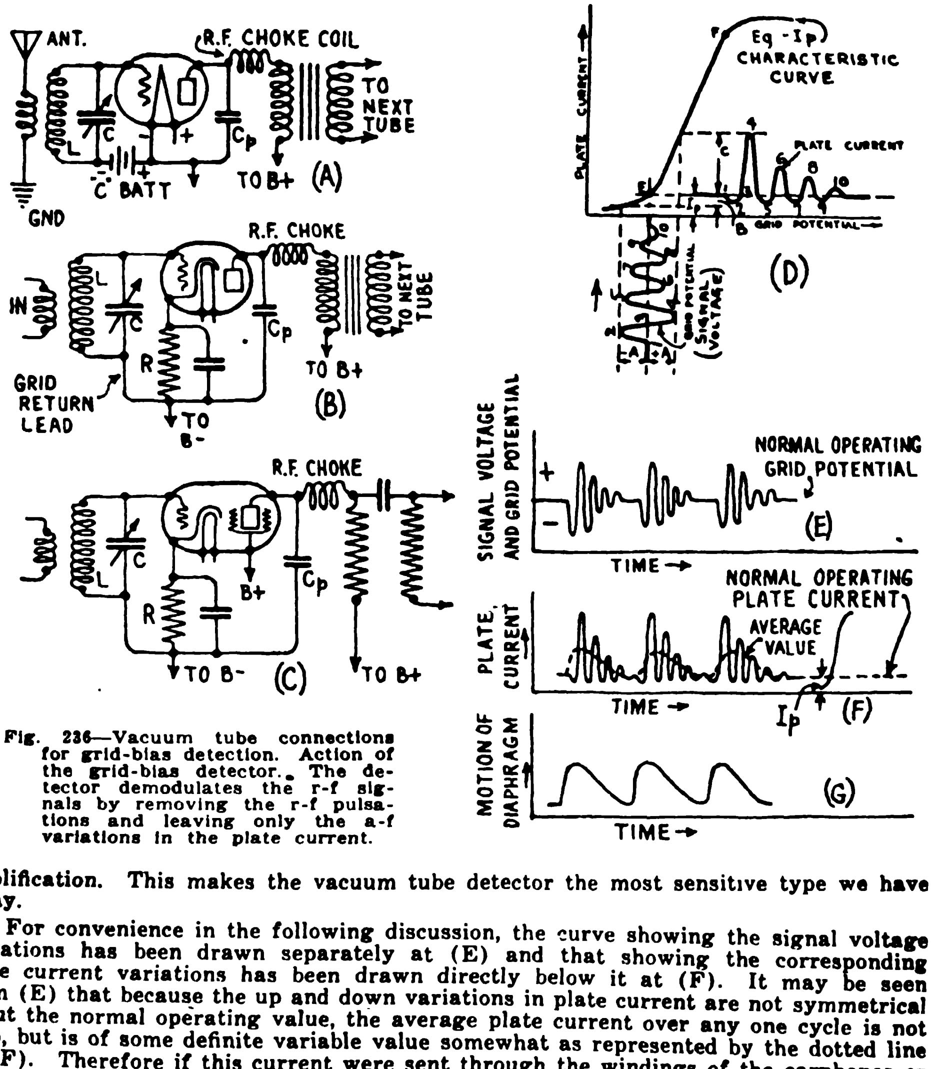


Fig. 236—Vacuum tube connections for grid-bias detection. Action of the grid-bias detector. The detector demodulates the r-f signals by removing the r-f pulsations and leaving only the a-f variations in the plate current.

amplification. This makes the vacuum tube detector the most sensitive type we have today.

For convenience in the following discussion, the curve showing the signal voltage variations has been drawn separately at (E) and that showing the corresponding plate current variations has been drawn directly below it at (F). It may be seen from (E) that because the up and down variations in plate current are not symmetrical about the normal operating value, the average plate current over any one cycle is not zero, but is of some definite variable value somewhat as represented by the dotted line at (F). Therefore if this current were sent through the windings of the earphones or a loud speaker, we would expect its diaphragm to vibrate in accordance with these average values on the dotted line. If, however, the plate circuit is shunted by a condenser C_p of suitable value as shown at (A), (B), and (C), it will act as a filter to smooth out the high-frequency variations in the plate current to a considerable extent, making the mean plate current value much higher and eliminating the radio-frequency

variations in the plate current. This is desirable when the detector is followed by an audio-frequency amplifier and especially so, when the audio amplifier is of the "resistance coupled" type as we shall see later.

The action of this plate circuit capacitance is very important in the operation of the detector. It can be seen that each time the grid potential swings still more *negative*, very little plate current flows, but on each *positive* half cycle of the applied signal voltage, a small increase in plate current takes place during the very small fraction of a second that the signal voltage has swung in the positive direction. By storing up current in the plate circuit condenser during these rapid pulses of plate current, and releasing it during the depressions, the variations are smoothed out by its filter action and the current actually flowing through to whatever device is connected in the plate circuit of the detector tube more nearly represents the gradual increase and decrease of the carrier wave which has been caused by the program transmitted. The plate circuit capacitance is really necessary as a high-frequency current storehouse to store electrons during the peaks of the plate current pulses and deliver them to the plate circuit during the depressions.

Care must be taken to see that condenser C_p which acts as a little storage reservoir, is of large enough capacitance to effectively store the tiny currents but not so large that it does not charge and discharge rapidly enough to keep in step with the r-f variations. If the condenser is of too large a capacitance it will charge and discharge too sluggishly and will affect the audio-frequency variations of the plate current and reduce the high audio notes. In order to assist the action of this condenser, a radio-frequency choke coil (of about 85 millihenries when a .0001 mf. condenser is used) is usually connected in the plate circuit as shown at (A), (B), and (C), the inductive action of this choke tending to oppose the high frequency changes in plate current. A choke and condenser used for this purpose are shown at the right of Fig. 124. They really form a low-pass filter as explained there. In most practical detector circuits, enough capacitance exists between the plate and cathode of the tube and between the plate and grid circuit of whatever device is connected in the plate circuit, to enable this action to take place even if no additional r-f choke coil and condenser are connected in the detector plate circuit, but the action is usually improved by the use of these extra parts. In many modern receivers, two condensers are connected across the r-f plate choke to form a more efficient low pass "pi" type filter as shown at (C) of Fig. 123.

It is evident then that the plate current actually flowing through whatever device is connected in the plate circuit of the detector is a pulsating direct current which varies in value in accordance with the *audio frequency* variations of the signal voltage impressed on the grid, as shown at (G). The plate filter blocks out all radio-frequency variations in the plate current. If this current were sent through the winding of a pair of earphones or loud-speaker, the diaphragm would move in accordance with the wave-form of (G) if the signal having the wave-form of (E) were impressed on the tube.

Hence, by operating the tube at the lower bend, the effect of every cycle of the signal voltage is to produce a certain *increase* and a much smaller *decrease* in the plate current, as shown by the plate current curve at (D). It is evident that the operation of the tube about the point F on the upper bend of the curve by putting a positive voltage or bias on the grid, would be similar to that on the lower bend, with the exception that at every cycle the incoming signal would produce a large decrease and small increase of plate current. However, the operation around the lower bend is preferable in practice and is used most, since the steady plate current I_p flowing in the plate circuit at all times is much smaller than in the case of the upper bend, so the current drawn from the "B" batteries (or other "B" power supply unit) is not so great, therefore saturation of the core due to this plate current flowing through the primary winding of the audio transformer which may follow is not so liable to happen. Another reason for not using the upper bend of the curve is that when the grid is made positive, considerable current may flow in the grid circuit. This is objectionable as we shall see in Art. 340. Also, with separate-heater type tubes, it is much easier to obtain a negative grid bias by means of the ordinary grid-bias resistor connection shown.

In the grid bias detection just described, it is evident that if there were no capacitance or inductance, in the plate circuit, the plate current would be a direct current varying in strength at radio frequency, that is, the same frequency as the applied signal voltage. If we consider detection to mean "demodulation" of the signal,

tnen is it evident that the tube itself really serves to *amplify* the signal only, the process of *detection* or *demodulation* taking place in the *plate circuit* by the action of the external plate circuit capacitance and inductance as explained. Therefore it is often called "plate rectification". While a detector tube does amplify the r-f signal somewhat, this r-f amplification may be rather small under conditions where the radio-frequency resistance of the plate circuit load is insufficient (see Art. 337).

Since the grid bias detector action depends upon placing the operating point of the tube at the bend of the E_g - I_p characteristic curve, it is necessary to make whatever adjustments are necessary to satisfy this condition. There are three ways in which the operating point may be moved up and down the plate current-grid voltage curve until the most pronounced bend, and most satisfactory detection condition are found. These are; first, by changing the grid bias; second by changing the plate voltage; and third, by changing the filament temperature. Since the latter is usually kept constant during the operation of a tube, the problem resolves itself into employing the proper grid bias voltage for whatever plate voltage is to be employed. Different types of tubes have different requirements in this respect. The exact values of grid bias to employ will be considered later, when discussing power detection.

330. Grid leak and condenser detection: In the grid leak and condenser method of detection, the demodulation of the signal takes place in the grid circuit of the tube. It is therefore called *grid circuit* rectification. The most common form of this circuit uses a *grid leak* consisting of a non-inductive high resistor of several million ohms, and a grid condenser usually of the mica dielectric type, connected in the grid circuit either as at (A) or (B) in Fig. 237. At (C) the equivalent connection for a separate-heater type of tube is shown. This circuit was for many years practically the only one in use—and it is still not altogether out of date. Some broadcast receivers still use it and most short-wave sets use it, but in the broadcast field it is being gradually replaced by the plate circuit detector.

There are several ways of explaining the action of this type of detector, all of them being rather complicated. In one, the action is considered on the basis of the grid current which flows. In the other one, the potentials on the grid are mainly considered. We shall explain it by the latter method. Let us first forget about the grid leak resistor R_g and see what happens in the circuit due to the flow of electrons in the various parts.

With this circuit, when no signal is being received, a steady plate current I_p flows from the plate to the cathode and back through the circuit, depending on the voltage of the plate and the temperature of the filament. If the grid return is to the positive side of the filament, the normal grid potential is at E, (usually slighty positive).

When a signal is received by the antenna, an alternating e.m.f. is set up across the coil and the plates of the tuning condenser C.

Let us refer to (A) of Fig. 237. During one half of each cycle, the signal e.m.f. causes electrons to flow out of plates 5 of the tuning condenser, around to 3 and 4 of the tuning coil and into plates 6 and the filament. Plate 2 of the grid condenser is positive because it has lost some of its electrons since during this half cycle the signal e.m.f. has made terminals 2, 5 and 3 positive. A part of the stream of electrons being emitted from the filament or cathode strike the grid. These electrons immediately

rush from the grid to condenser plate 1. The insulation (dielectric) of the grid condenser prevents the electrons that go into plate 1 from crossing over to plate 2.

During the next half cycle, the signal e.m.f. in L is reversed, electrons therefore rush from 6 to 4, to 3, and into 5 and 2, but the electrons that have already collected on the grid, and condenser plate 1 during the first half of the cycle cannot go anywhere, that is, they are trapped on the insulated part of the circuit comprising the grid and the one plate of the grid condenser. The stream of negative electrons coming over from the filament on their way to the plate repels them, since they are also nega-

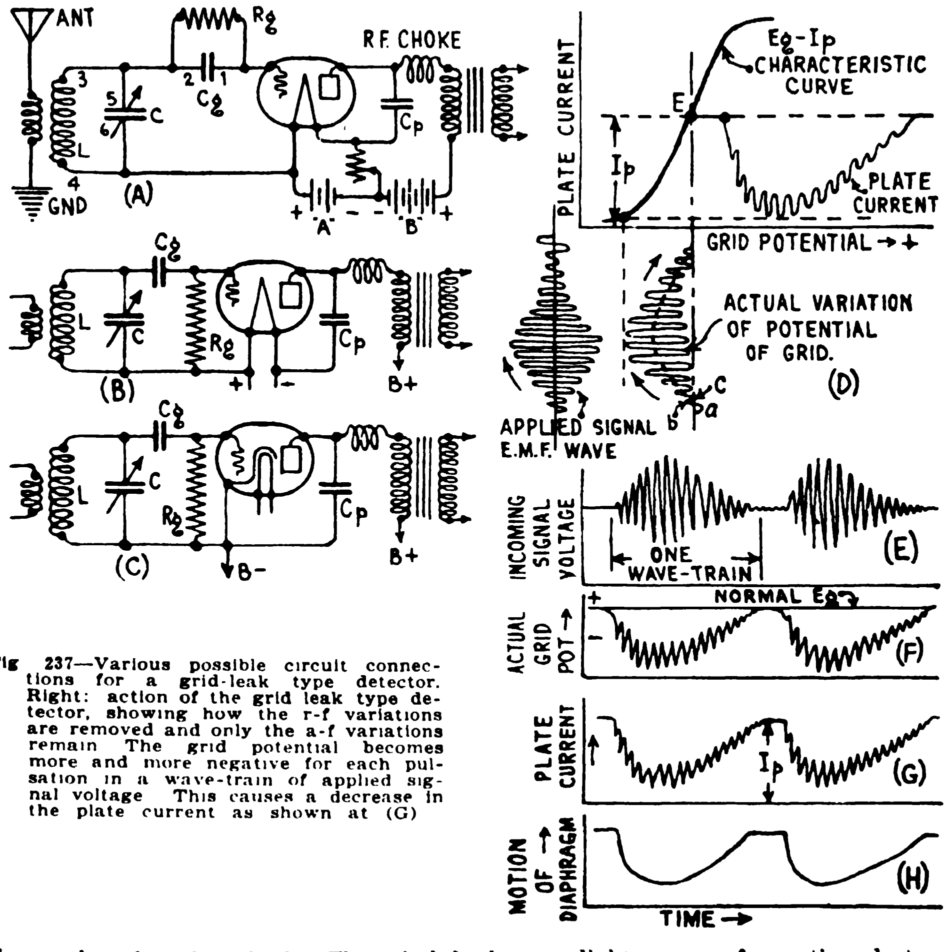


Fig 237—Various possible circuit connections for a grid-leak type detector. Right: action of the grid leak type detector, showing how the r-f variations are removed and only the a-f variations remain The grid potential becomes more and more negative for each pulsation in a wave-train of applied signal voltage This causes a decrease in the plate current as shown at (G)

tive, and pushes them back. There is left then, a slight excess of negative electrons or negative charge on the grid and plate 1 at the end of the first cycle. During the next cycle of the signal voltage the same thing is repeated and there is left a slightly greater excess of electrons on plate 1 and the grid. As the number of electrons accumulating on the grid and plate 1 increases during each cycle, the mean potential of the grid becomes more and more negative, and the plate current is therefore becoming smaller and smaller. This would go on for a number of cycles of the signal voltage until so many electrons have collected on plate 1 that their charge would react on the grid and prevent any more electrons entering the grid from the filament. The tube then becomes blocked and no further action can take place on the grid until some means is provided for the excess of electrons to escape from plate 1 of the grid con-

denser. We do not want the tube to block in this way, but want the negative charge on the grid to be cumulative only during the number of r-f cycles which constitute a positive (or a negative) half of the *audio cycle*, and then we want the grid to be free to build up a new potential corresponding to the next half of the audio cycle, and so on. Then we will have accumulated grid voltages varying according to the audio-frequency, and the plate current will vary similarly. Moreover, the amplification factor of the tube will be employed and we will obtain both demodulation and amplification.

This is accomplished by connecting a very high resistance (in the neighborhood of a million ohms) either across the grid condenser as at (A), or between the grid terminal of the tube and the filament as at (B), or the cathode as at (C). The action is exactly the same for either of the connections. Since the resistance is high, the electrons flow through it at a rather slow rate because the resistance opposes their motion. This high resistance is called the *grid leak* because it provides a path for the trapped electrons to "leak" through it from the grid to the filament or cathode. The leak should have just enough resistance in combination with the grid condenser capacitance used, to allow the excess of electrons to leak off before the next signal impulse comes in. The entire action just described takes place very rapidly during the time it takes for one *wave train* of the signal to come in. A wave train comprises all the r-f variations in signal voltage taking place during the time one cycle of the audio or voice current modulation takes place. This is illustrated at (E). For instance, for a station broadcasting with a carrier frequency of say, 1,000,000 cycles per second (300 meter wavelength), there would be 1,000,000 divided by 2,000, or 500 r-f cycles for each single cycle (lasting 1/2000 of a second) of an audio note of 2,000 cycles being transmitted. That is, in a single wave train represented in (D) and (E), there would actually be 500 r-f oscillations occurring during the short period of 1/2000 of a second. It is really impossible to picture such rapid action in our minds.

Now let us see what has happened to the plate current during this time. We have seen that for each cycle of the signal e.m.f. coming in, the grid grows more and more negative due to the accumulation of the trapped electrons on it. The more negative the grid becomes, the more it reduces the plate current. Throughout a series of r-f signal voltage cycles then, the average plate current grows less and less as shown by the plate current curve at (D). Also, the grid potential, instead of varying exactly in accordance with the applied signal voltage variations as it does when a grid condenser is not used (see (D) of Fig. 236), now goes up to *a* in the positive direction, then down to *b*, then up to *c*, and so on. During each cycle, the ***average*** grid potential decreases. The result is that the plate current, instead of varying up and down symmetrically, grow less and less with each cycle of a wave train and follows along a dipping current curve as shown at (D) and (G), having little ripples in it for each r-f cycle of the incoming signal. It is evident that since the plate current has these little r-f ripples or variations in it as shown at (G), the use of the low-pass filter system consisting of the condenser C_p alone, or this condenser with the r-f choke coil in series with the plate as shown at (A), will smooth out these ripples in the same way as described in the discussion of the grid bias detector. The plate current will then vary as shown at (H) for the signal voltage wave shown at (E), the r-f ripples having been removed by the plate circuit condenser C_p. The diaphragm of the earphones or loud speaker through which this current flows will also move back and forth in accordance with this, and the wave form of the sound it produces will be the same.

For the action just described to take place, it is necessary that the grid be positive at least during a part of each cycle as signals come in, in order to attract some of the electrons emitted from the filament. The grid may however be connected to the negative end of the filament (or to the cathode in a separate heater type tube). It will then have the same potential as the filament or cathode, and its voltage will become momentarily positive during part of each wave train as signals come in.

It is evident that in the grid leak and condenser method of detection, the demodulation process takes place in the grid circuit. Consequently this is usually called ***grid circuit rectification***. In this system, the radio-frequency signal voltage applied to the input is really changed to audio-frequency variations in grid potential, and the audio-frequency variations are amplified in the plate circuit. Because of this amplification, this type of detector is more sensitive than the grid bias type. The grid condenser and grid leak resistance must be so proportioned that the electrons causing the grid charge cannot leak off through the leak path to any appreciable extent in the extremely short time between any two cycles of the incoming r-f signal voltage; but so the

electrons do leak off during the time over which one *wave train* is being received. A "wave train" may include from several hundred to a thousand or more cycles of the r-f signal voltage. The grid leak connection shown at (B) and (C) is especially advantageous in present-day single control receivers as we shall see later. High-grade grid leaks having permanent and accurate values of resistance should always be used. A grid leak whose resistance varies, will cause crackling and frying noises while receiving a program. The resistance element is usually enclosed in a glass tube with metal end-caps for connection and is designed to snap into metal clips furnished on the grid condensers. A typical grid condenser and grid leak resistor are shown in Fig. 238. The value of grid leak resistor used must have a low enough resistance to allow the accumulated negative charge on the grid to leak off during the interval between the wave trains. Its resistance must be high enough to prevent the charge from leaking

Fig 238—Grid condenser with clips into which the grid leak resistor at the right may be snapped.

off the grid too rapidly, in which case there would be only a small change of plate current produced and the signal strength as heard in the phones would be reduced. For weak signals, such as are received during long-distance reception, a tube is much more sensitive if higher resistance grid leaks are used. In either case, if a grid leak having too high a resistance is used it will result in excessive accumulation of negative charge on the grid, blocking the action of the tube, or making the signals sound mushy. This is usually accompanied by a characteristic "cluck-cluck-cluck" sound in the phones or loud-speakers as the charge leaks off at intervals through the insulation between the tube elements, tube prongs, etc. The values of grid leaks and condensers to use will be discussed in Article 333.

331. Square law and linear detectors: Due to the fact that the amount of amplification which could be applied to the incoming r-f signal voltages by the r-f amplifiers in use several years ago was very small, the typical radio set of that time employed a grid leak-grid condenser type of detector that was intended to operate with a radio-frequency input voltage of 0.1 volt or less. These detectors operated with low plate voltages of from 45 to 90 volts. Operation was entirely along the *curved* portion of the plate current-grid voltage characteristic. Such detectors give non-uniform response since in most cases the voltage appearing across the plate circuit load is proportional to the *square* of the input signal voltage. Therefore, doubling the signal voltage input produces 2 x 2 or 4 times the output, etc. Such detectors are called *square law* detectors because their output follows the "square" law. This would seem to be a big advantage, and from the standpoint of sensitivity in loud signals it is, but from the angle of tone quality it is a disadvantage.

When a detector follows a square law, it produces some second harmonic distortion which is proportional to M/4, where M is the percentage modulation of the r-f signal. The distortion consists of production of the second harmonics (double frequencies) of the notes actually being transmitted, and also all the possible sum and difference frequencies. Thus if the transmitting station is simultaneously transmitting notes of 2,000 and 2,500 cycles, the output of the square law detector in addition to con-

taining these desired frequencies, will also contain the double frequency components of 4000 and 5000 cycles, and the sum and difference components of 4,500 and 500 cycles. When the signal is modulated 100 per cent, this distortion reaches a maximum of 25 per cent. Under this extreme condition these distortion components would be 25 percent as large as the desired components, so that weak-signal detection of signals that have a high degree of modulation will not give satisfactory results from this point of view. The present tendency in broadcasting is to increase the modulation to 100 per cent, at least on the loud *fortissimo* passages of music being broadcast, so as to utilize as completely as possible, the output of the transmitter. Most of the larger stations are now using 100 per cent modulation. Grid leak detectors operating at low plate voltages, being square law detectors, will produce too much distortion of the 100 per cent modulated signals received from these stations.

This is one of the reasons why linear detection is being used more and more. A detector is *linear* when the audio frequency output voltage appearing across its plate circuit load is directly proportional to the r-f signal voltage input. Thus a signal input three times as great produces an output voltage three times as large etc. Such detectors are absolutely essential for distortionless detection. The ordinary power detector of either the grid leak or grid bias type has approximately such a characteristic and so gives substantially undistorted rectification.

332. Power detection: A *power detector* is one that will not overload when very large r-f input signal voltages are applied to its grid circuit, and which will handle considerable electrical *power* in its output. Power detectors are usually operated with rather high voltages. Either a grid bias type or a grid leak and condenser type of detector may fulfill the conditions of power detection if they are operated properly.

Receivers built during the early days of radio employed two or three stages of tuned radio-frequency amplification using the three electrode tubes of the 201-A, 226, or 227 type which were the only ones available at that time. It was impossible to secure much amplification per stage with these tubes, because of the difficulty of preventing oscillation due to feedback in the tubes themselves, and other forms of feedback coupling. Therefore, the signal was not very strong when it reached the detector, and it was necessary to use at least 2 stages of audio-frequency amplification after the detector in order to make the signal strong enough to operate a loud speaker satisfactorily. Now that it is possible to build high-gain r-f amplifiers without oscillation troubles, thanks to the screen-grid tube, in modern receivers the signal voltage is first amplified greatly before it reaches the detector. It is not uncommon to use 5 and 6 high-gain amplifier stages before the detector, both to obtain high gain and the necessary number of tuned circuits for satisfactory selectivity. Therefore the detector must handle quite large signal voltages without distortion, and in most cases feeds directly into a single power output audio stage and then to the loud speaker. It is in receivers of this kind that *power detectors* must be used, for the signal voltages are entirely too large to be handled by the old forms of detectors. In some cases, the loud speaker may even be operated directly from the output of the detector without employing any audio amplification. Linear and power detectors are very closely

related in practice, since they usually go together, although no detector has a perfectly straight-line characteristic. In the usual meaning of the term, "power detector" is used in connection with detection when the r-f signal voltage applied to the detector input is at least 1 volt or more.

333. Grid leak and condenser power detection: According to the information obtained by Mr. F. E. Terman from several thousand tests on power detectors (the results of which were published in the Dec. 1930, I. R. E. Proceedings), power detectors of the grid leak and condenser type can be made to produce satisfactory detection under all conditions, provided the proper values of plate voltage, and grid leak and condenser are employed. The proper values for suitable weak signal detection are different from those for strong signal detection. Some of this data is reviewed here.

"When a radio-frequency signal of at least several volts amplitude is applied to a suitably adjusted grid-leak detector, the action taking place in the grid circuit is different from the action for voltages less than 1 volt. The rectified grid current charges the grid condenser negatively and causes the average grid potential to have a negative value. This average value is always such that the positive crests of the signal make the grid go positive a small amount. Each time the grid goes positive, grid current flows, and makes up for the current that leaks off through the grid leak during each cycle.

At times when the signal amplitude is decreasing in size, it is necessary that the grid leak allow the grid condenser charge to leak off at a rate that will cause the average grid potential to reduce at least as fast as the signal amplitude is changing. This requirement calls for values of grid condenser capacity and leak resistance smaller than usually used.

If high-quality output is to be obtained from the grid-leak power detector, it is necessary to have the proper grid leak and condenser combination. Suitable values for any tube are, a grid leak of about ¼ megohm and a 0.0001-mfd. grid condenser. With these proportions the average grid potential will be able to change as fast as the signal amplitude, up to modulation frequencies of 5000 cycles.

The overloading point of the grid-leak power detector is reached when plate rectification causes increase of plate current, while grid rectification causes decrease of plate current. Plate rectification thus neutralizes the grid action and causes distortion.

As the maximum amplitude of a fully modulated wave is twice the carrier amplitude, a particular tube will handle half as big a carrier wave acting as a power detector as it can amplify, using the same plate voltage in both cases. Thus, a 201A-type tube with 90 volts on the plate usually uses a 4½-volt C bias. The peak amplitude of carrier wave that can be handled at a plate voltage is one-half of this, or about 2¼ peak volts.

The maximum audio-frequency power output obtainable from the grid-leak power detector is slightly over one-fourth of the undistorted power the tube can give as an amplifier at the same plate voltage and a suitable grid bias. Thus, the 210-type tube at 247½ plate volts will put out 340 undistorted milliwatts as an amplifier, and will put out about 100 undistorted audio milliwatts as a power detector.

The approximate audio-frequency output of a grid-leak power detector can be obtained by a simple computation. It is apparent that the average grid voltage of the power detector follows the modulation of the signal. This variation in average grid potential applies an audio-frequency voltage to the grid of the detector tube, and it is this audio-frequency grid voltage when amplified by the tube acting as an amplifier that constitutes the audio-frequency output of the detector.

In the ideal detector, the audio-frequency voltage applied to the grid would be equal to the modulation voltage in the signal. If the degree of modulation is m, and the carrier amplitude is E_o, the ideal amount of modulation voltage is mE_o. The actual power detector is only about 75 to 85 per cent perfect, and will apply to the grid an audio-frequency voltage about 75 to 85 per cent of mE_o. The percentage tends to rise slightly as the signal amplitude becomes large, but under ordinary conditions it is surprisingly nearly constant at this approximate range for all tubes.

In order to deliver power, the detector tube must operate with a high plate voltage. At the same time, the bias of the grid leak power detector is approximately zero except when the signal is coming in, and so the allowable plate current sets a limit to the plate potential. Tubes such as the 201A, 112A, and 227 can operate as power detectors with 90 to 135 volts on the plate, and under such conditions will handle an r-f voltage of at least 2 volts on the detector grid without distortion. When a 227 or 224

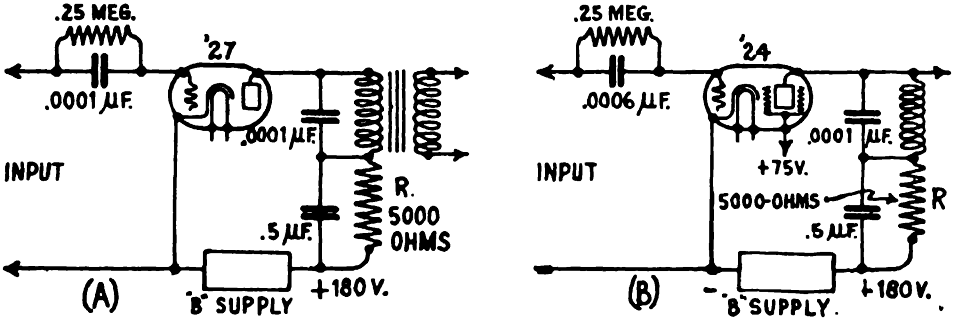


Fig. 239—Connections for '27 and '24 type tubes as grid leak-condenser type power detectors.

type grid-leak condenser detector is to operate with small signal voltages (under 1 volt) applied to the grid, the grid condenser should be of .00025 mf. capacitance and the grid leak should be of 1 megohm, with a plate voltage of 180 volts in each case, with the grid return to cathode. This is for broadcast band reception. When used in this manner with small input voltages, it will be necessary to have one stage of audio-frequency amplification between the detector and the input to the power tube. This is because the detector output with weak signals is not sufficient to properly load up the power tube. By changing the proportion of the grid-leak and grid-condenser size it is possible to operate the power tube directly from the output of a suitable detector tube for strong signal voltages. Values of .0001 mfd. for the grid condenser and 250,000 ohms for the grid leak resistor with the grid return leak returned to a negative grid bias of about 1 volt should be used with these tubes. It will be noted that these proportions are different than those for weak signals.

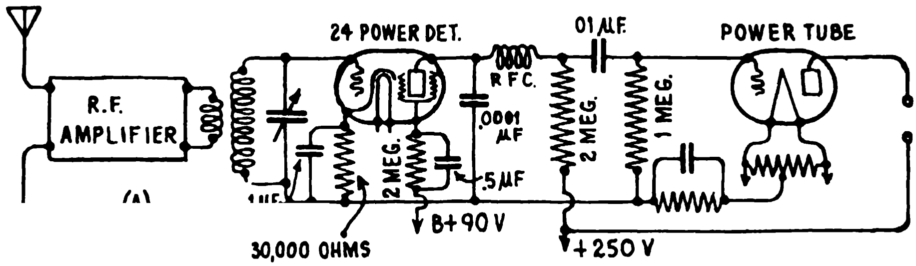
A means of avoiding the effect of high plate current when high plate voltages are employed in this method, is shown in Fig. 239 for both '27 and '24 type tubes. With no signal, since the grid has no bias voltage, the plate current would be rather high. Therefore, the plate voltage is dropped through the resistor R so that the plate current is at a safe value. The incoming signal provides a negative bias, lowering the plate current. This cuts down the drop through R, and allows the full plate voltage to be effective. The '27 and '24 type tubes should be operated with the values shown, with the grid return directly to the grounded cathode. The effi-

ciency of rectification in either case is about 85%. The grid circuit puts a load resistance of about 150,000 ohms (with a 0.25 meg. leak) on the tuned circuit ahead of it. This is higher than with the old types of weak-signal grid leak detector.

334. Grid bias power detection: In the grid bias type of power detectors commonly used, rather high plate voltages and negative grid bias voltages are employed. The amount of grid-bias voltage usually applied in power detectors of this type is roughly about 10% of the plate voltage value.

The '24 type screen-grid tube may be used as a power detector in this way by applying a plate voltage of 180 volts or more. If the load resistance is half megohm or more, it is safe to apply as much as 250 volts from the B power supply device. As the plate impedance of the tube operated this way is high, the only way to place a sufficiently high load impedance in its circuit is to use a resistance of half megohm or greater, as shown at (A) of Fig. 240.

When the load resistance and the plate voltage have been fixed, it is only a question of fixing the grid bias and the screen voltage. Both depend on the applied plate voltage and on the resistance in the plate circuit as well as on each other. If a potentiometer of fairly high resistance, say 30,000 ohms, is connected from the screen-return to the "grounded" grid-return, and the cathode is connected to the slider, it is always



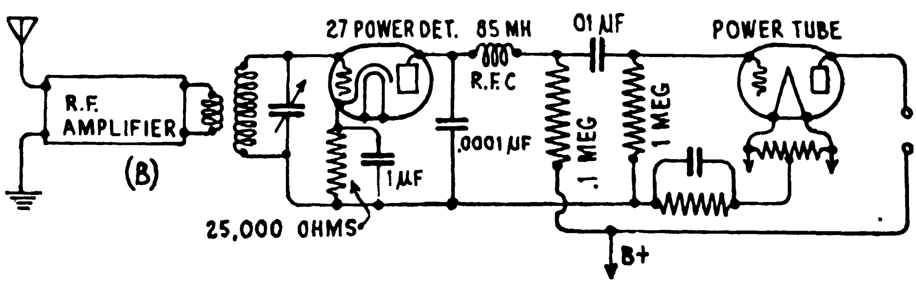


Fig. 240 (A) Grid bias power detector with '24 type a-c screen-grid tube.
(B) Grid bias power detector with '27 type a-c 3-electrode tube.

possible to find the best combination for either best detection or best amplification. If this method is adopted, the combined potentiometer and screen terminal should be connected to B + 75 volts. If the potentiometer method is not used, it is best to give

the screen a voltage of about 45 volts and then adjust the grid bias until the detecting efficiency is the best.

As far as detecting efficiency is concerned, the same may be obtained with a large number of combinations, even when the voltages are very low, say 45 volts on the plate with correspondingly lower voltages on the other elements. But for power detection, it is necessary to make them high as suggested above. A by-pass condenser of about 2 microfarads should be connected across that portion of the potentiometer which is in the grid circuit and one of about 1 mfd. across the other portion. If a by-pass condenser is connected across the load resistance, it should be very small because a small condenser is very effective across a resistance of half megohm.

If a fixed grid bias resistor and fixed screen voltage are employed as shown at (A) a grid bias resistor of 20,000 to 30,000 ohms may be employed. The screen-grid voltage may be obtained as shown, being actually about 45 volts positive. The '27 tube may be used as a power detector with quite satisfactory results if a special transformer is used to couple this tube to the power tube. The a-c plate resistance is rather high, so it is necessary to use a special coupling unit.

If desired, the '27 type power detector may be resistance coupled to the power tube as shown at (B) with less gain. The usual grid bias resistor for a '27 tube operated this way is 20,000 or 30,000 ohms at a plate voltage of 180 volts. Some set manufacturers use as low as 12,000 ohms. The resistor should be by-passed with a condenser having a capacitance of at least 1 mf. as shown.

The '27 type tube may be operated as a very sensitive and efficient grid bias type power detector by connecting it as shown at (A) of Fig. 241. With this arrangement, the '27 type tube is almost as efficient as the '24 type screen-grid detector and is able to handle quite a large signal-voltage input to its grid circuit without overloading. For instance, at an input signal voltage of 9 volts R.M.S., the output signal voltage across the 80 henry choke L is 40 volts R.M.S. at the values of plate voltage and grid bias shown, for a 30% modulated signal. The value of grid bias resistor shown, places the normal grid voltage at 10.9 volts negative. If a plate circuit "resistance load" is to be employed instead of the inductance L, the values should be as follows; plate voltage applied by B power supply=250 volts; grid bias resistor 20,000 ohms; plate circuit resistor 200,000 ohms.

335. Multiplex linear power detector: A form of linear power detector in which a two element or "diode" connection of a '27 type tube is employed is shown at (B) of Fig. 241.

The "diode" detector consists of a 227 tube with its grid and plate connected together to form in effect a single plate. As its function is merely that of a linear detector and it does not amplify since there is no grid, it is supplemented by the '27 type tube marked "det-amp.". In the "diode" rectifier, the marked curvature, at low values of applied signal voltage, causes distortion unless the input level is maintained high enough to avoid excursions into the curved range. In other words, we must maintain operation on the straight-line portion of the characteristic.

The peculiar input circuit, common to all diode detectors and shown in this circuit, is made necessary by the high damping (or low input resistance) of the tube when operated in this fashion. The high damping factor, limiting the gain in the previous r-f stage, the low output efficiency (not to be confused with rectifying efficiency)

and other factors all contribute to the need for a high-gain a-f amplifier, as evidenced by the fact that three audio stages usually follow the "diode" detector.

Diodes have the advantage of a long-range of distortionless straight-line operation, as compared with a comparatively small curved portion of the characteristic. This advantage has led to their use in several commercial receivers.

335A. Comparisons of detector arrangements: A comparison of "power" and "weak-signal" detection shows that the former is superior in that it introduces less distortion, is a more efficient rectifier, gives less disturbance with strong static impulses, and results in an increase in the

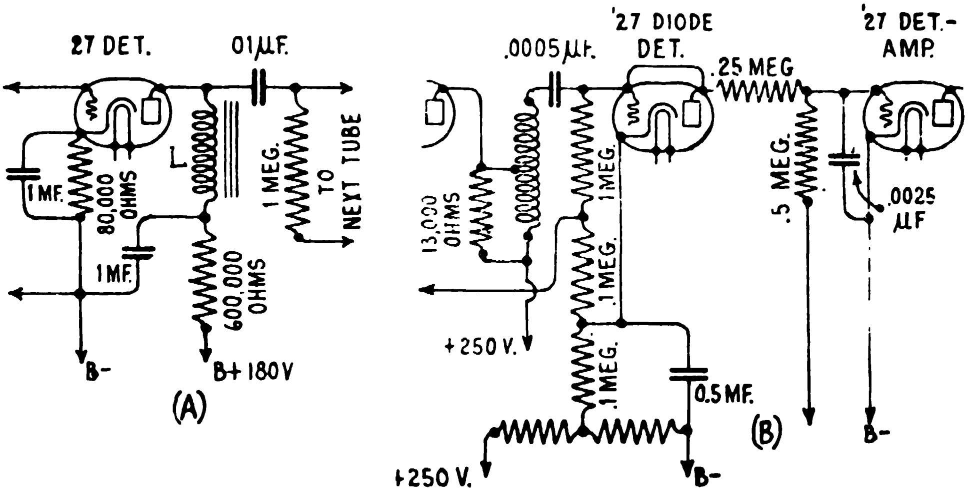


Fig 241—(A) Connections for '27 type tube as a sensitive linear detector capable of handling large signal voltages
(B) Connections of "Multiplex" diode linear power detector.

effective selectivity. The linear power detector is obviously here to stay, and the future will see it used more and more. It has even been suggested that some day the input to the loud speaker will be obtained by rectifying a very large radio-frequency signal of perhaps 100 volts, using a vacuum tube, or perhaps a copper-oxide element, without the use of any audio-frequency amplification at all.

Power detection requires more radio-frequency amplification than does the weak-signal detector, and not many years ago this was a real disadvantage. The screen-grid tube has altered the situation however, by making it comparatively simple to obtain high radio-frequency amplification per stage without trouble from regeneration. Inasmuch as it is still necessary to use the same number of tuned circuits in screen-grid sets as before, in order to obtain the necessary selectivity, the additional radio-frequency amplification is so easy to obtain that it is a great advantage.

336. Vacuum tube amplifier action: Vacuum tubes used in modern radio receivers serve three purposes, they amplify, they detect or de-

modulate and they rectify. We have studied detector action, and will now consider the action of the tube as an amplifier. As explained in Articles 283 and 284, a vacuum tube having a grid may be used as an amplifier when connected in suitably arranged circuits, because any voltage variations impressed in the grid or input circuit are reproduced on a much larger or amplified scale across any impedance connected in the plate

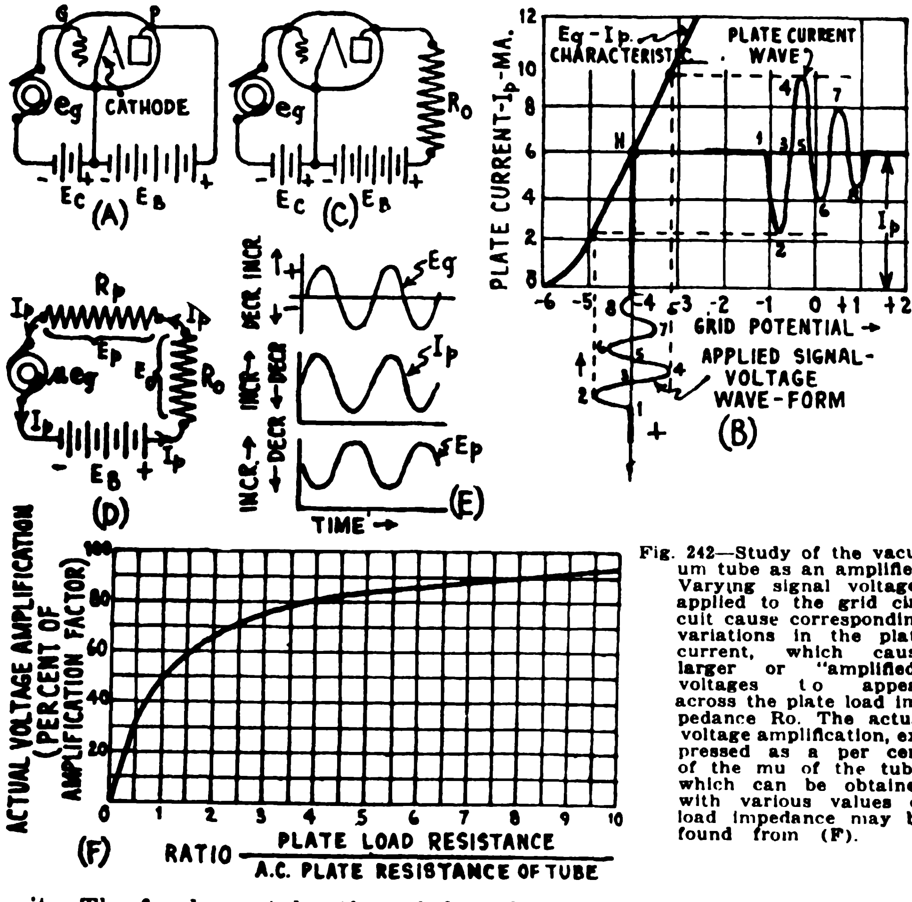


Fig. 242—Study of the vacuum tube as an amplifier. Varying signal voltages applied to the grid circuit cause corresponding variations in the plate current, which cause larger or "amplified" voltages to appear across the plate load impedance Ro. The actual voltage amplification, expressed as a per cent of the mu of the tube, which can be obtained with various values of load impedance may be found from (F).

circuit. The fundamental action of the tube as an amplifier was discussed in the previous articles referred to, but it will be studied more in detail now. We will now see just how a tube amplifies voltage variations applied to its grid circuit,—and how much.

In order to understand the action of the tube as an amplifier, let us refer to (A) of Fig. 242. Here a vacuum tube is connected with its proper plate and grid potentials as shown. The filament voltage may be neglected since it serves no purpose other than to supply heating current to the filament. In our discussions of vacuum tubes as amplifiers, we will

show ordinary three-electrode tubes for simplicity in the diagrams, but it should always be kept in mind that the same actions take place in 4-electrode screen-grid tubes and 5-electrode pentode tubes unless otherwise specified. Let e_g be the alternating signal voltage applied to the grid circuit, represented here simply by an a-c generator. It is evident from our previous discussions of vacuum tube action, that the application of this signal voltage to the grid will cause the grid potential to vary about the mean grid potential which is due to the steady grid bias voltage applied to the tube, and this in turn will cause variations in the plate current.

To understand just what takes place let us refer to (B) which represents the E_g - I_p characteristic curve of the tube for some particular fixed value of plate voltage. It shows the plate current in milliamperes for any value of grid potential. Let us assume that the steady grid bias voltage supplied by the grid bias source E_c is 4 volts negative. This sets the operating point of the tube at H on the characteristic curve, and a steady plate current of 6 milliamperes flows. Now let us suppose that an a-c signal voltage as represented by the signal wave-form shown at the lower part of (B) is applied to the tube. The effect of the individual cycles of this signal voltage will be to add and subtract from the steady grid bias voltage, and so vary the potential of the grid. For instance, when the signal voltage varies negatively from point 1 to 2, it causes the grid potential to change from -4 to almost -5 volts. This causes the plate current to decrease from point 1 to point 2 on the plate current curve. When the signal voltage increases positively from points 2 to 3 to 4, the plate current increases from corresponding points 2 to 3 to 4 as shown. It is evident that the result of the application of the a-c signal voltage is to cause the plate current to rise and fall above and below its steady normal no-signal value of I_p. When the grid potential decreases (is made more negative) the plate current decreases; when it increases (is made less negative) the plate current increases. Therefore the plate current variations are in phase with the grid potential variations. If a load resistance is connected in the plate circuit as shown at (C), when the plate current increases due to an increased grid potential, the voltage drop $I_p R_o$ across the resistor R_o increases, and for this reason the voltage E_p actually applied to the plate decreases. That is, the true plate voltage *decreases* when the grid potential *increases*, and it *increases* when the grid potential *decreases*. Hence, the plate voltage and grid potential variations are 180°. out of phase. The phase relations of these three factors are shown at (E) of Fig. 242. They should be remembered as they are very important in some considerations of amplifiers. It will be noticed that the plate current changes produced by this signal voltage are quite large. Since the applied plate voltage is steady in value, it is evident that the effect of variations of the grid potential i really to vary the internal resistance of the plate-cathode path in the tube. This variation of the internal plate resistance causes the plate current to vary. All the applied plate circuit voltage appears as a voltage drop between the plate and cathode.

In order to make these large plate current variations useful, it is necessary to connect some form of resistance or impedance, called the *plate circuit load*, in series with the plate current, so that the varying plate current flowing through this impedance will produce varying falls of potential through it, the varying falls of potential being communicated to another circuit in either of several ways (by transformer coupling, resistance coupling, or impedance coupling as we shall see later). At (C) an impedance R_o of some sort, (shown here simply by a resistance symbol and considered as a resistance for simplicity in the following discussion), has been connected in the plate circuit. The changing plate current must flow through this plate load impedance as well as through the internal plate impedance R_p of the tube. This changing current flowing through these impedances causes a voltage drop to appear across each; E_p appears across the plate-cathode and a voltage drop E_o appears across the load R_o. The voltage drop across each part is of course proportional to the impedance of that part. In order to simplify the visualization of the action, engineers prefer to consider the tube circuit drawn in simple form as at (D) of Fig. 203. Here the grid circuit with its applied signal voltage, is replaced by a small a-c generator put right in the plate circuit. The voltage of this schematic generator is equal to the voltages of the applied a-c signal multiplied by the amplification factor (mu) of the tube, i.e., μe_g. This is so,

because any change in voltage of the grid has the same effect on the plate current as a voltage "mu" times as large acting directly in the plate circuit (see Articles 283 and 284). The internal impedance of this generator is equal to the internal plate impedance of the tube. This equivalent tube circuit is shown in simplified form at (D) of Fig. 242.

We have already considered the effect on the tube action of the varying voltage drop through the plate circuit load. We found in Article 292 that it was the cause of the "dynamic" characteristic of the tube being different than the static characteristic. We are now interested in finding the conditions for maximum *voltage amplification.*

337. Maximum voltage amplification: In a vacuum tube amplifier it is of course desirable to obtain as much amplification as possible. Therefore, it is important to know just what circuit conditions are necessary in order to obtain maximum amplification, and just how much this amplification will be.

Referring to (D) of Fig. 242, let I_p be the plate current flowing at some particular instant and R_p and R_o be the plate and load resistance respectively. Let e_g be the grid potential at the instant considered. The e. m. f. of the plate battery E_b is then all used up in sending the plate current through these two resistances and is equal to the potential drop $I_p R_o$ through the load resistance, plus the potential drop $I_p R_p$ between the plate and cathode of the tube. This latter drop is E_p. Thus:

$$E_b = E_p + I_p R_o$$

from which

$$E_p = E_b - I_p R_o$$

which expresses the difference of potential between the plate and cathode of the tube. (Whether these two voltage drops can be added together by simple arithmetic or not depends on the nature of the load. In fact the very properties of the combined circuit depend on the kind of impedance for which R_o stands. For instance, it may stand merely for a simple non-inductive resistance, or for a more or less complicated tuned circuit, etc. We are considering merely the simple case with resistance load.)

Suppose now, that the grid potential e_g is varied so as to increase the current I_p in the plate circuit; then the resistance drop $I_p R_o$ in the plate load will increase correspondingly. It then follows from the above equation, and from a consideration of the simple series circuit, that with the battery voltage E_b remaining constant, the *actual effective plate potential* E_p will *decrease*. Conversely, when I_p is *decreased* by decreasing the grid potential, the effective plate potential E_p will *increase*. The greater the load resistance, (or more generally the greater the load impedance Z), the greater the variation of effective plate potential E_p resulting from a given change of plate current I_p, brought about by a given variation of grid potential e_g. This is plainly shown in the "dynamic characteristic" curves at (A) of Fig. 210 where it may be seen that the slope or slant of the dynamic characteristic curve *decreases* as the resistance (or impedance) of the external plate load is *increased*. As an extreme case, for infinite load impedance, the curve would be parallel to the grid voltage axis, showing that the variations of grid potential would produce no variation of the plate current, but would produce *maximum* variations of plate potential. Since the voltage across the plate load at each instant is equal to the fixed B battery voltage minus the plate potential existing at that instant, it is evident that the voltage variations across the plate load are *amplified variations* of the grid or (input) *potential variations.*

If the load is a non-inductive resistance R_o, the total plate circuit resistance is R_o+R_p. Therefore, the *change* in plate current (amps.) produced by the signal voltage μe_g (referred to the plate circuit) is determined by

$$I_p \text{ (change)} = \frac{\mu e_g}{R_o+R_p}$$

This varying current flowing through the load resistance R_o produces a change of voltage across it of

(Load voltage change) $e_o = I_p R_o = \dfrac{\mu e_g R_o}{R_o + R_p}$

but the ratio of this output voltage appearing across the load, divided by the input signal voltage e_g, is the voltage amplification G, produced by the tube. Hence:

$$G = \frac{e_o}{e_g} = \mu \frac{R_o}{R_o + R_p}$$

If the second part of this equation is very large (i.e., approaches unity) the value of G will be very nearly equal to the amplification constant of the tube. When R_o is infinitely great, the voltage amplification becomes actually equal to the amplification factor of the tube. This is the *maximum* amplification that can be obtained from the tube. But this is only theoretical, since an infinitely great resistance constitutes an open circuit, and under such conditions there would be no voltage applied to the plate and the tube would not function. To be strictly correct then, we should state that the voltage amplification approaches more closely to the theoretical maximum value, namely, the value of the amplification factor, as the value of the load resistance is raised, until such a point is reached that the mean plate potential becomes too low to allow the tube to function properly. It is of course impossible to build primary windings of coupling transformers, or coupling impedances to have infinite impedance in practice, so the full "mu" of the tube is never realized. Practically, however, it is possible to obtain quite a large fraction of the "mu" of the tube. For instance, if the resistance of the load is made three times the plate resistance of the tube, then since the load resistance is ¾ of the total resistance and the plate resistance of the tube is ¼ of the total resistance, the voltage amplification will be ¾, or 75% of the "mu" of the tube. In this case, if the plate resistance is 15,000 ohms, the voltage appearing across a coupling resistance of 45,000 ohms will be equal to the signal voltage times 75 per cent of the "mu" of the tube. If the load resistance equals the a-c plate resistance of the tube, half the amplification factor of the tube is obtained. The larger the plate circuit load is made, the greater is its ratio to the total resistance, and therefore the greater will be the voltage amplification. At (F) of Fig. 242, the actual voltage amplification as a percentage of the amplification factor, is plotted on the vertical scale; and the scale on the horizontal axis is plotted with the ratio of the plate load resistance to the a-c plate resistance of the tube. This curve is applicable to any tube. From it, the voltage amplification as a percentage of the mu of the tube may be found if the ratio of the load resistance and the a-c plate resistance of the tube are known. This is reproduced here by courtesy of "Wireless World Magazine."

When considering a tube which has a very high plate resistance, it is evident that any ordinary amount of resistance put in series in its plate circuit makes little difference to the *variations* in the plate current. For example, a '27 type tube with a

plate resistance of 9,000 ohms would have about the same variations in plate current if a load of 1,000 ohms were added to the plate circuit. But if another 9,000 ohms, or even more were added, the variations in the plate current would decrease. In other words, the mutual conductance of the circuit, i.e., the relation between the variations in the plate current and the variations in the input signal voltage, decreases.

The plate resistance of a '35 type screen-grid tube, for instance, is about 350,000 ohms. Its mutual conductance is about 1100 micromhos. Now if a load resistance of 50,000 ohms is connected in series with the plate circuit of the tube, the plate current variations will only decrease by about ten per cent, and the mutual conductance will decrease the same amount.

We can say, then, that with a high-resistance tube, the mutual conductance of the circuit is about the same as for the tube with no-load resistance, that the variations in the plate current in the entire circuit is equal to the alternating grid voltage multiplied by the mutual conductance, and that the voltage amplification from such a tube is equal to the product of the mutual conductance and the load resistance. Thus: variations in current (with or without load) $= E_g \times G_m = \dfrac{\mu e_g}{R_o + R_p}$.

Voltage amplification $= G_m \times R_o$.

It is interesting to note that the maximum amplification that can be secured from a three-element tube working into a resistance is the mu of the tube, but that the maximum amplification obtainable from a screen-grid tube depends not so much upon its amplification factor but upon the mutual conductance. This is because the load resistance that can be built up for the tube to work into is limited—we cannot get resistances beyond perhaps 200,000 ohms in an r-f circuit at broadcast radio-frequencies, or much less than this figure at higher frequencies.

Example: (a) A 227 type tube ($R_p = 9{,}000$ ohms, and "mu" $= 9$) is being worked into a plate load of 27,000 ohms. What is the actual voltage amplification; (b) If a 10 volt signal were applied to the grid, how much would the plate current vary? (c) What would be the variation in voltage drop across the load resistor?

Solution: (a) actual voltage amplification, $G = \mu \dfrac{R_o}{R_o + R_p} = 9 \times \dfrac{27{,}000}{27{,}000 + 9{,}000} = 6.7$

(b) plate current variations $= \dfrac{\mu e_g}{R_p + R_o} = \dfrac{9 \times 10}{27{,}000 + 9{,}000} = .0025$ amps, or 2.5 ma.

(c) load voltage variations $= .0025 \times 27{,}000 = 67.5$ volts. Ans.

It is evident from the foregoing, that in order to obtain a large percentage of the voltage amplification possible from an amplifier tube, the impedance of the plate load into which it works, must be as large as possible. This should be remembered. If instead of a resistance R_o, an inductive load is connected in the plate circuit of the tube, the varying output voltage across it will depend not only on the magnitude of the signal voltage variations applied to the grid, but also on their frequency, because the impedance of an inductance increases as the frequency increases, since $X_l = 2\pi fL$. If the resistance of the load is high compared with its reactance, the discrimination toward certain frequencies is lessened, and the amplification approaches that obtained with a resistance load.

338. Conditions for undistorted amplification: In our consideration of the action of the vacuum tube as an amplifier at (B) of Fig. 242, no mention was made of distortion which may be produced in the wave-form

of the plate current due to various factors which may affect the operation of the tube. In the case shown, the form of the plate current variations is an exact enlarged duplicate of the signal voltage variations applied to the grid i.e., this is no *distortion*. This is so, because the proper grid bias voltage (for the particular plate voltage employed) was purposely selected so that the normal operating point H of the tube would fall at the middle of the comparatively straight part of the E_g - I_p characteristic. An amplifier tube should always be operated this way. The negative grid bias voltages specified for the various tubes at the various plate voltages given, in Fig. 214, are those which place the operating point at this middle point on the curve, and should always be employed when using tubes as amplifiers.

Thus if we desire to operate say a '24 type tube as an amplifier using a plate voltage of 180 volts, referring to Fig. 214, we find that a grid bias voltage of 1.5 volts (negative) must be applied to the grid. This makes the tube operate at approximately the center of the straight part of its characteristic curve when no signal is applied to the grid.

The conditions for undistorted amplification are (a) the grid bias and magnitude of the a-c input signal voltage must be such that the tube operates only over the straight part of its E_g - I_p characteristic; (b) the load resistance must be large with respect to the internal plate resistance of the tube R_p. We shall now see what happens if these operating conditions are not observed.

339. Distortion due to incorrect grid bias: In the case shown at (B) of Fig. 242, the grid bias voltage was correct, so the tube operated over the straight portion of the characteristic curve and distortionless amplification was produced

Suppose the negative grid bias voltage applied to the tube is too great, as in (A) of Fig. 243, so that when a signal voltage is applied to the grid as shown, the negative half cycles of the signal voltage cause the grid potential to swing so far negative that the tube is operated on the lower curved part of its characteristic where the plate current changes are *not* proportional to the grid potential changes. As can be seen from the diagram, the curve showing the resulting plate current variations, is no longer similar in shape to that of the grid (signal) voltage, and its average value is no longer equal to the plate current I_p flowing during the zero signal condition, as is true when the bias is such that the input signal voltage carries the grid operating point only over the straight part of the curve. The parts of these curves representing the decreases in plate current, are partly shut off; and distortion results because the plate current changes caused by the equal positive and negative halves of the signal voltage cycles are not equal (or are not amplified alike) The average plate current is now greater than that during the no signal condition, as shown

If a milliammeter were connected in the plate circuit of a tube operating this way, as shown at (B), it would show an *increase* in the plate current when signals were applied to the grid, or when a particularly loud signal came through; an indication of distortion due to too much grid bias voltage This method of indicating distortion is a very simple and effective one and is used especially for detecting distortion in the tubes in audio amplifiers. This will be considered in Article 344.

If the negative grid bias applied to the tube is great enough, and the input signals are strong enough, the grid may be forced so far negative on strong signals that the plate current may be reduced to zero altogether on the negative half cycles. This will produce even worse distortion since the tube would now be operating under the conditions shown at (D) of Fig. 236, i.e., the tube is operating as a grid bias detector instead of as a distortionless amplifier Rectification of this sort taking place in r-f amplifier stages due to the loud signals from local stations may produce cross-modulation. This will be studied later.

If the grid bias voltage is too small, the tube may operate near the upper bend of the curve around E, and distortion again occurs as shown at (C) of Fig. 243 due to the fact that when the positive half cycles of the signal occur, the tube is operating on the curved part of the characteristic where the changes in plate current are not proportional to the

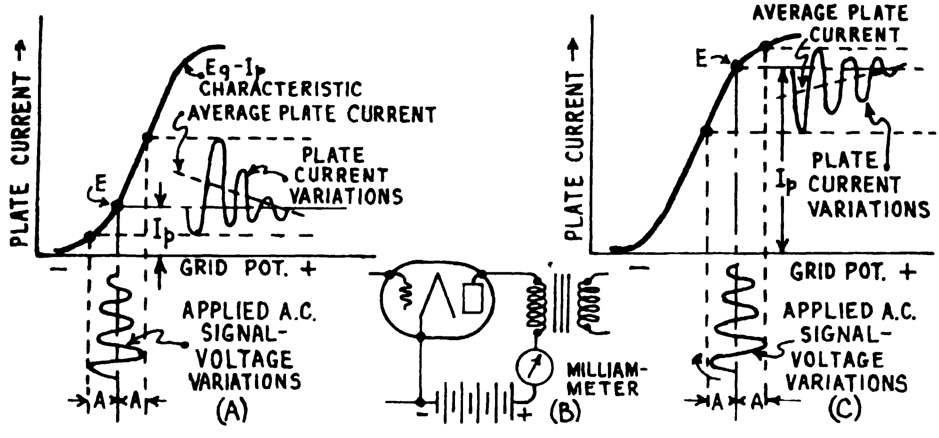


Fig 243—(A) Distortion of wave-form of plate current, resulting from excessive negative grid bias
(B) Connection of plate circuit for indicating tube distortion
(C) Distortion of wave-form of plate current, resulting from insufficient negative grid bias

changes in grid potential. The result is that the average plate current (shown by the dotted line) is now less than the normal no-signal plate current I_p. If a milliammeter is connected in the plate circuit, the needle will kick *down* every time a loud note comes through. This indicates distortion due to operation at the upper bend of the characteristic curve.

340. Distortion due to positive grid: It is possible for an amplifier tube to be operating with such a grid bias voltage, that the positive half cycles of the a-c signal voltage applied, are not great enough to drive the grid potential to the extreme positive potential illustrated at (C) of Fig. 243, where the tube operates at the upper bend of the characteristic. It may just drive the grid slightly positive each time as shown at (A) of Fig. 244. We shall now see that even this condition will cause distortion. The E_g-I_p characteristic curve is no longer straight after positive potentials are applied to the grid, it begins to curve downward, and at high enough positive grid potentials, it becomes practically horizontal as shown. Distortion will occur as soon as the positive half cycles of the input signal voltage make the grid positive. The reason for this is as follows:

As soon as the grid becomes positive with respect to the cathode, it acts exactly like a plate and attracts some of the negative electrons being emitted by the cathode. These electrons flowing to the grid and down through the grid circuit to the cathode, constitute a current in the grid circuit. This grid circuit current must flow through the

resistance of the electrical apparatus connected in the grid circuit (secondary of preceeding coupling transformer, etc.). There is then, an I R drop in the grid circuit due to this, so that at each instant, the potential of the grid is not equal to the applied signal voltages but is equal to this value minus the voltage drop in the input circuit due to the grid current—just as the effective plate voltage applied to a tube is not the voltage of the B battery, but is this voltage minus the voltage drop in the output load resistance. The greater is the input signal voltage, the more the grid goes positive on each positive half cycle, the greater is the voltage drop in the grid circuit resistance, and the smaller is the proportion of the signal voltage that is actually effective on the grid. The voltage drop due to grid current really prevents the actual grid potential from swinging as far positive as it otherwise would on the positive half cycles of signal. The result of this is that the increases of plate current due to the positive half cycles of the signal are not as great as they otherwise would be, the plate current variations are not exact enlarged duplicates of these signal voltage variations, and therefore distortion has taken place. This may be seen from (A) in Fig. 244. If the grid did not go positive and cause a grid current to flow, the actual potential variations would be along points 1-7-3-8-5-9 etc. of the signal voltage wave, and the plate current variations would follow along points 1-7-3-8-5-9 of the plate current wave. Actually however, since there is a voltage drop in the grid circuit each time the grid becomes positive, the grid potential does not swing as far positive as points 7-8-9, etc. would indicate, but only swings out to points 2-4-6 as shown by the dotted line. Likewise the plate current changes only swing to points 2-4-6 on the plate current curve. Evidently, distortion takes place.

For the reasons shown above, the grid of a tube operated as an amplifier should never be allowed to go positive in ordinary circuits, or distortion will result. The selectivity of an r. f. amplifier circuit is materially reduced if the grid goes positive, since the voltage drop produced in the secondary of the tuning coil due to the grid current, materially reduces the

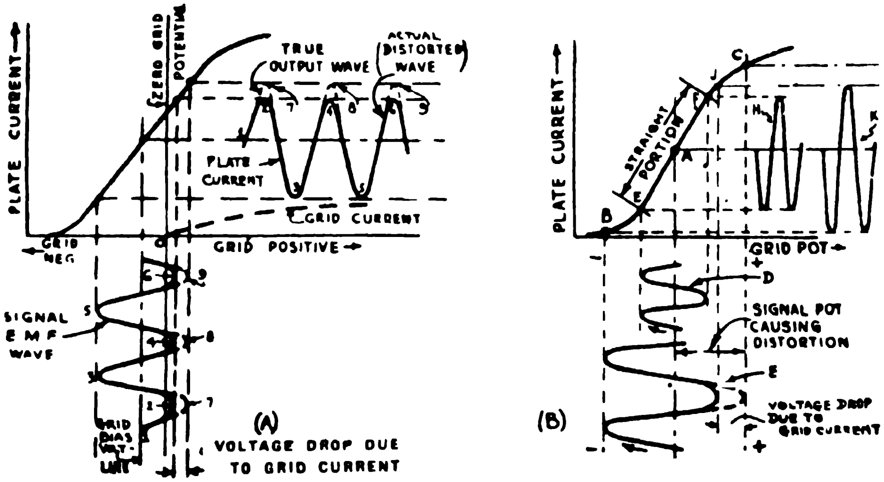


Fig. 244—(A) Distortion of the wave-form of plate current due to signal voltage driving the grid positive.
(B) Distortion of the wave-form of the plate current due to too large a signal voltage applied to the grid circuit

signal potential (of the desired station) actually applied to the grid. Since this decreases the signal response of the desired station, a decrease in selectivity results. Therefore it should be carefully remembered that

any amplifying tube should be so operated that the grid will at all times be kept negative under the usual signal conditions. This is another reason for using the proper value of negative "C" bias. The "C" bias values given in Fig. 214 are the proper ones recommended by the tube manufacturers. Notice that the "C" bias recommended increases as the plate voltage is increased. This will be readily understood by referring to the graphs at the right of Fig. 197. The characteristic curves for the higher plate voltages fall above and to the left of those for the lower voltages. Therefore the normal operating point of the grid must be shifted to the left by using higher "C" bias voltages, when high plate voltages are employed.

341. Distortion due to overloading: Even though the grid bias voltage applied to the grid of an amplifier tube is such that the tube operates at the certain point A of the straight portion of its characteristic curve as shown at (B) of Fig. 244, distortion may result if the signal voltage is so large that it drives the operating point of the grid down to the lower bend of the E_g - I_p characteristic curve or makes the grid positive during the positive half cycles of the signal. This is the condition where the tube is overloaded, i.e., too large a signal voltage is being applied to its grid circuit. This condition is shown at (B).

If a relatively small signal voltage D is applied, since it causes the grid potential to vary only over the straight portion of the characteristic curve between points E and F (and the grid is always negative), no distortion takes place, as shown by the fact that the curve H showing the plate current variations produced, is an exact enlarged duplicate of the signal-voltage curve D. If a very large signal voltage E is applied, distortion may occur due to two causes. First, the grid potential is driven over the upper bend of the E_g - I_p characteristic, and second, since the grid is driven positive during each positive half cycle of the signal e. m. f., a grid current flows, causing a voltage drop in the grid circuit so that instead of the grid potential moving up to point C on the curve each time, it actually only moves to point J. The resulting distorted plate current variations are shown by curve K.

In a case like this, since the average plate current is increased during the negative half cycles, and is decreased during the positive half cycles, the pointer of a milliammeter connected in the plate circuit would kick up and down violently every time a loud passage was received, indicating distortion due to overloading of the tube.

342. Distortion due to curved characteristic: In the tubes which are used to deliver *power* to a load, such as a loud speaker, etc., distortion may also occur due to an excessively curved E_g - I_p characteristic at the lower part, caused by using a plate load having too low a resistance. This will be considered later when studying power tube circuits.

343. Results of tube distortion: The result of the various forms of distortion which may result by operating the tube in any manner which will cause the tube to operate over the curved part of its characteristic, is to make the wave-form of the plate current variations, and magnified output voltage variations across the plate load, different from that of the applied signal voltage. This means that the sound waves produced by the loud speaker due to these currents, will not be a duplicate in every respect of those impressed on the microphone in the broadcasting station. Hence the necessity for avoiding all forms of distortion. The output current or

voltage variations produced as a result of severe distortion may be very complex and very much different from those of the input signal voltage.

When a tube distorts, it adds to the output circuit, certain frequencies which are not present in the input. The currents of all of these frequencies added together at any instant equals the actual total plate current at that instant. The combination of all the wave-forms of these harmonics produces the resulting wave-form of the actual plate current.

The *maximum permissable grid swing* is the range of voltage on the grid which will not cause distortion either because of the grid going positive or because of the operating point traversing the lower bend. By "grid swing" is usually meant the *total* swing of grid voltage due to both the positive and negative halves of the a-c input voltage cycles. Thus, if the grid swing is 5 volts it means that the potential of the grid varies 2.5 volts above and 2.5 volts below some fixed value, a total swing of 5 volts. In this case, 2.5 volts is what we ordinarily refer to as the "peak" voltage of the a-c. Unfortunately, in many cases the term "grid swing" is also referred to as the maximum or peak value of the a-c signal voltage in one direction from zero (see (A) of Fig. 69). Obviously, the grid swing by this definition is half of that in the former case. It would be best to refer to the *total* grid swing by the former definition, and refer to that of the latter definition by the term "peak voltage". In order that no distortion be produced in a vacuum tube operating as an amplifier, the grid bias voltage is made *at least* as large as the "peak" value of the applied signal voltage in one direction, so that even when the positive half of each cycle is being received, the grid does not go positive. The grid bias voltage should preferably be a little greater than this value, in case extra strong signal impulses should be received during the rendering of a musical selection, etc. The grid swing must of course be referred to the dynamic characteristic curve of the tube.

344. Testing for distortion: One of the simplest methods of testing for distortion occuring in amplifier tubes, in order to determine the cause, and remedy it if possible, is by connecting a d-c milliammeter of suitable range depending on the plate current of the tube to be tested (see Fig. 214) in the plate circuit of the tube, as shown at (B) of Fig. 243. Of course the moving coil and pointer have too much inertia to be able to follow the individual variations of each cycle of the plate current, but they will follow the *average* values of the current. As explained in the previous articles, when a signal starts to come in or when a particularly loud musical passage or speech sound is being received, the cause of the distortion will be indicated by which way the pointer of the milliammeter deflects or "kicks". These may be summarized as follows:

(1) meter pointer kicks *downward*—too small a negative grid bias.

(2) meter pointer kicks *upward*—too great a negative grid bias.

(3) meter pointer fluctuates up and down—too large a signal voltage swing being applied to the grid of the tube.

A fluctuation of meter reading of over 10 per cent from its normal

steady value should be taken as an indication of distortion which is bad enough to be noticeable to the average human ear.

The remedy for case (1) is either to increase the negative grid bias voltage on the tube, or increase the plate voltage, or if these adjustments are not possible in the particular amplifier being considered, to reduce the input signal voltage applied to the tube. The remedy for case (2) is to decrease the grid bias voltage or the plate voltage, or else decrease the incoming signal voltage applied. The remedy for case (3) is obviously either to increase the grid bias and plate voltages until a longer straight portion of characteristic is available; reduce the signal voltage; or use a different type of tube having a longer straight portion of characteristic i.e., one able to handle larger signal voltages. There is also another remedy for case (3), that of connecting two amplifier tubes in push-pull so that only half the total signal voltage is applied to each tube in turn. This circuit will be considered in connection with audio amplifiers in Art. 447.

REVIEW QUESTIONS

1. Why is detection or "demodulation" necessary in a radio receiver?
2. Explain briefly, the action of the grid-bias type of detector. Draw a sketch showing an alternating signal voltage wave applied to the grid circuit of a grid-bias detector and by projecting up to the E_g - I_p curve of the tube, construct the resulting plate current curve.
3. Why is it preferable to operate the tube at the lower bend of the curve in grid bias detection?
4. Show by means of circuit sketches, how the necessary negative grid bias voltage may be obtained for operating the following types of tube as grid-bias detectors: (a) 3-electrode direct-heater type; (b) 3-electrode separate-heater type; (c) screen grid direct-heater type; (d) screen grid separate-heater type.
5. Explain briefly, the action of the grid leak and condenser type of detector. Draw the same kind of a sketch for this type, as described in question 2
6. What is the purpose of: (a) the grid condenser; (b) the grid leak resistor, in this type of detector?
7. What is meant by "square law" detection Why is it objectionable under present broadcasting conditions?
8. What is linear detection? What type of detector is practically a linear detector?
9. What is meant by power detection? How does a power detector differ from the ordinary forms of detectors used several years ago. What recent change in radio receiver design has led to the extensive use of power detection?
10. Draw circuit sketches showing the following types of tubes ar-

ranged for grid leak and condenser power detection, and also separate sketches showing the arrangement for grid bias power detection: (a) 227; (b) 224; (c) 232.

11. Why may a grid leak and condenser detector be made more sensitive than a grid-bias detector?
12. What would happen if a high-gain r-f amplifier were employed ahead of a low-voltage type of detector such as was commonly used several years ago, if the r-f amplifier applied a signal voltage of about 5 volts to the detector?
13. Explain (with diagrams) the action of the vacuum tube as an amplifier. Why is it necessary to connect an impedance in the plate circuit to secure useful amplification from a tube?
14. What must be the value of the load connected in the plate circuit of an amplifier tube in order to obtain an amplification equal to the amplification factor of the tube?
15. It is desired to obtain 90 per cent of the possible amplification from a '24 type tube operated at a plate voltage of 180 volts. Its "mu" is 400 and its a-c plate resistance is 400,000 ohms. What load resistance is required?
16. A 10 volt signal is applied to the grid circuit of the above tube. What voltage variations appear across the load resistance?
17. Explain how detection or "demodulation" may occur in an improperly adjusted radio-frequency amplifier.
18. How must an amplifier tube be operated in order to secure distortionless amplification insofar as the tube itself is concerned?
19. What will be the effect on the wave form and the average value of the plate current of an amplifier tube if (a) it is operated with too great a negative grid bias voltage; (b) too small a grid bias voltage; (c) too great a signal? Illustrate each answer by means of a sketch, assuming a sine-wave voltage applied to the grid circuit, for simplicity.
20. Explain how a milliammeter connected in the plate circuit of an amplifier tube may be used to indicate when distortion is present in the tube and just what is causing the distortion. Illustrate your answers with sketches. If the milliammeter pointer deflects to a steady position when the signal is being received, what does this indicate?
21. A pure sine-wave sound of 1,000 cycles is played before the microphone in the broadcast studio. This is transmitted by the station, and is received and amplified at a receiving station. The r-f amplifiers in the receiver are being operated at an excessively negative grid bias. Will the sound heard in the loud speaker be different than that at the microphone? Give reasons for your answer, and show with sketches, just what the waveform of the received signal current will be after it has been amplified. Compare this with that of the original sound.

CHAPTER 21.

RADIO FREQUENCY AMPLIFICATION

NEED FOR AMPLIFICATION — REQUIREMENTS OF THE RECEIVER — STRENGTH OF THE RECEIVED SIGNAL (MICROVOLTS PER METER) — DESIRABLE FIELD STRENGTHS — TYPES OF R-F RECEIVING SYSTEMS — TUNED RADIO-FREQUENCY AMPLIFICATION — MULTIPLE TUNED R-F — RESISTANCE COUPLED R-F AMPLIFIER — PLATE IMPEDANCE COUPLING — GRID IMPEDANCE COUPLING — PARALLEL PLATE FEED — SELECTIVITY OF MULTIPLE STAGES — DESIRABLE TUNING CURVE SHAPE — HOPKINS BAND REJECTOR SYSTEM — THE BAND SELECTOR — BAND SELECTOR SYSTEMS — CROSS-MODULATION AND PRESELECTOR — VARIABLE TUNING CONDENSERS — SHAPES OF CONDENSER PLATES — S.L.C., S.L.W., S.L.F. CENTRALINE CONDENSERS — REDUCTION OF TUNING CONTROLS — EFFECT OF ANTENNA ON SINGLE CONTROL RECEIVERS — CONDENSER GANGING — EQUALIZING THE CIRCUITS — PURPOSE OF THE VOLUME CONTROL AND ARRANGEMENTS — AUTOMATIC VOLUME CONTROL — COUPLING IN THE "B"-SUPPLY — AUTOMATIC TUNING AND REMOTE CONTROL — THE SUPERHETERODYNE RECEIVER — REVIEW QUESTIONS.

345. Need for amplification: Now that we have studied the operation of the tuned circuit and the construction, characteristics, and operation of vacuum tube detectors and amplifiers, we are prepared to consider the various types of amplifiers employed in radio receivers for strengthening the weak signal voltages set up in the antenna circuit by the passing electromagnetic radiations.

At (C) of Fig. 180 a simple receiving circuit employing a crystal detector was shown. In this receiver a tuned circuit was employed to separate the signals of the desired station from those of all other stations, by so adjusting the tuned circuit that it was in resonance at the frequency of the carrier current of the desired station. Under this condition, the tuned circuit offered minimum impedance to the flow of currents of this particular frequency, and a much higher impedance to currents of all other frequencies (from all other stations). In this way the currents from all other stations were suppressed and the current from the wanted station was allowed to build up quite strong voltages across the tuned circuit, these being applied to the detector and causing operation of the earphones. In this circuit there is no voltage amplification other than any slight gain due to the tuned circuit, so that the loudness of the signal heard in the phones is entirely dependent on the strength of the signal received in the antenna circuit, the design of the primary-secondary coupling and that of the tuned circuit.

In (A) of Fig. 236 and (A) of Fig. 237, a vacuum tube was used as a detector or demodulator in place of the crystal detector. Since the vacuum tube not only performs the function of demodulation, but also amplifies the input signal voltages somewhat, the signals heard in the phones are somewhat stronger than when the crystal detector is employed. A set of this type gives fairly satisfactory earphone operation from power-

ful broadcasting stations located short distances away. Since the amount of energy decreases very rapidly as the distance from the transmitting station is increased, it is evident that a simple one-tube set of this type cannot be used for long-distance reception because the very weak voltages induced in the antenna circuit are not strong enough (even when amplified by the detector tube), to operate the earphones. Increased sensitivity can be obtained by the use of regeneration, but there is a very definite practical limit to this.

The use of earphones has become unpopular, as people desire to hear radio programs in comfort with loud speakers which produce enough volume of sound to be heard clearly in rooms of large size. Loud speakers require a stronger operating current than ordinary earphones do, since they do more work in setting a larger amount of air in motion. A large volume of sound from a loud speaker represents the expenditure of a great deal more energy than is ever picked up by the antenna, and therefore the energy delivered to the speaker must be supplied by some local source in the receiving equipment, and the rate of expenditure of this local energy must be controlled in such a way that it varies as nearly as possible in exact accordance with the varying amplitude of the high-frequency voltage generated in the antenna circuit by the passing fields. This extra energy may be added most conveniently by means of vacuum tubes operated as amplifiers. Of course the extra energy in this case really comes from the B-power supply device used with the tubes. In order to accomplish this, the varying signal voltage is applied to the input or grid circuit of the vacuum tube. The amplified signal-voltage variations appear across whatever load is connected in the plate circuit of the tube, (see Art. 336 and Fig. 242).

The next question to be settled is just where to introduce the amplification. It is evident that we have two choices in this matter. Assuming the use of a vacuum tube as the detector or demodulator, we could amplify the weak radio-frequency signal voltage variations before they are fed to the detector (*radio-frequency amplification*). The tendency in receiver design has been to amplify the radio-frequency signal voltages before they are applied to the detector and also amplify the audio output after leaving the detector. This arrangement is still used, but as a result of the development of satisfactory high gain screen-grid amplifier tubes, power detectors, and pentode power tubes, the tendency has been to increase the radio-frequency amplification used ahead of the detector, and use less audio amplification after the detector, on account of the many advantages of the former. It is not unlikely that receivers of the future will not employ any audio amplification at all, all of the amplification being applied to the signal voltage variations before they are fed to the detector. This will necessitate the development of suitable detector tubes or other demodulation devices (not necessarily of the vacuum tube type), which are also capable of efficiently applying a large amount of undistorted power directly to the loud speaker. In order to understand why amplification ahead of the detector is so advantageous, we must see just what the radio receiver is called upon to accomplish.

346. Requirements of the receiver: (1) The modern receiving set must separate the signals of any station it is desired to hear, from those of all other stations. The *selectivity* of a receiver is a measure of this ability to discriminate between the wanted and unwanted signals. Of course we would like to have a receiver which will respond only to one given station at a time, and not at all to any other, no matter how powerful the undesired signal is, or how close in frequency it is to the desired signal. This perfect selectivity is very difficult, if not impossible to attain in practice, but we now have receivers which are as selective as we really need them under present broadcasting conditions.

(2) The receiving equipment must also amplify the incoming signal voltage of the desired station until sufficient energy is available to operate the loud speaker as loudly as desired. The *sensitivity* of a receiver is a measure of the overall amplification from the antenna-ground terminals of the receiver to the loud speaker. Needless to say, it is desirable to have the sensitivity as high as possible, for then it requires but a small input signal voltage to deliver considerable output power to the speaker. It is also true however, that a sensitive receiver without adequate selectivity is useless, for the more sensitive it is, the more stations it tends to bring in at once with loud speaker volume and therefore the greater is the need for eliminating the signals of these unwanted stations.

There is another very definite limitation to the amount of sensitivity required. The combination of all noises coming into a radio receiver is usually taken to be the *noise level*. These noises are caused by true static, electrical interference, by re-radiating receivers, or by any apparatus or device which produces electrical impulses which may be picked up by the receiver. The limit of radio reception is governed by the distance and power of the transmitter and also by the stray electrical disturbances which drown out the signals as soon as the intensity of the latter falls to a certain degree. A point is reached where the signal from the station has less strength than these stray impulses forming the *noise level*. It is then impossible to receive the station without this interference, because the receiver will amplify the noise voltages equally as well as it amplifies the true signal voltages, since they are of the same electrical nature.

(3) A receiver must also reproduce in the form of sound waves, the exact wave-form of the sound set up in the broadcasting studio. The *fidelity* of a receiver is a measure of how well it reproduces the actual sound wave originating in the broadcasting studio. If a note of a certain loudness and frequency is sung into the microphone, then this note when reproduced by the loud speaker of the receiving equipment should be exactly the same both as regards wave-form, frequency and intensity. This should be true for any sound within the range that may be broadcast. In other words, a receiver that delivers a perfectly undistorted signal is one which has a uniform or flat frequency response curve from the antenna to the loud speaker output. This considers the loud speaker as part of the receiving equipment—which it most certainly is. Of course, this assumes that the equipment in the broadcasting station does not cause any distortion. In modern high-class stations, this is so nearly true that we may assume that their output is perfectly undistorted. Most transmitters now being constructed have an audio frequency range of 30 to 10,000 cycles with very small deviation from uniform frequency amplification over this range. While receivers which are perfect as regards the above three considerations, are practically impossible to attain in practice, many present day receivers are so sensitive, selective and produce such excellent frequency response (the average ear would not detect the small distortion present) that very satisfactory performance is obtained.

347. Strength of the received signal (microvolts per meter): We have already studied the factors which affect the energy radiated from the antenna of the transmitting station. We found that since this energy spreads out over a large area in all directions, the amount available at any receiving antenna to set up voltage in it is extremely small even when the

transmitting station is only a few miles distant. In order to compare the strengths of the signals received from various stations and the sensitivity of various types of receivers, it has become a practice to call the *voltage* that is induced in the receiving antenna, the ***field strength*** of the transmitter at that particular point on the earth's surface. The voltage set up in the average antenna is usually a few thousandths of a volt (millivolt). Since the voltage induced in a higher antenna will be greater than that set up in a lower one, it has become standard practice to rate field strength as so many *microvolts per meter*, or so many ***millivolts per meter.*** Micro-volts is commonly used, because the e. m. f. induced in an antenna is so small, that the use of the volt as a unit would necessitate the use of decimals in most cases. Thus, an antenna having an effective height of one meter, (1 meter is slightly over 3 feet) and having 10 microvolts induced in it is located in a field strength of 10 microvolts per meter. An antenna 5 meters high and having a voltage of 10 microvolts induced in it, is situated in a field of strength of 10 divided by 5, or 2 microvolts per meter, etc. The *effective height* of an antenna bears little relation to the actual height in meters of the antenna. It depends on many things—how well the antenna is insulated, the kind of soil over which it is erected, etc. The effective height of an antenna is somewhat less than its actual physical height above the ground and in most receiving measurements it is assumed as an average of 4 meters (13 feet). Of course the greater the field strength existing at the location of the receiving antenna, the more the volume one can get out of a receiver. Likewise, with a greater field strength, less amplification is required to produce a given output from the receiver.

348. Desirable field strengths: According to Dr. Alfred N. Goldsmith, (proceedings of the I. R. E. Oct., 1926) the type of reception to be expected with various field strengths at the receiving antenna is as follows:

Signal Field Strength (millivolts per meter)	Grade of Reception
0.1	poor reception
1.0	fair reception
10.0	very good reception
100.0	excellent reception
1,000.0	extremely strong reception

Antenna Power (watts)	Reception Range (miles)
5	1
50	3
500	10
5,000	30
50,000	100

From the point of view of signal strength, it is of course desirable that the transmitter stations employ considerable power so as to send out intense fields which are much stronger than those set up by static dis-

turbances, electrical appliances and other devices. The signal voltages will then be stronger than those set up by these sources of electrical interferences and the latter may easily be suppressed.

349. Types of r-f receiving systems: In order to obtain the amount of amplification necessary for satisfactory loud speaker volume, it is usually necessary to employ more than one amplifier tube. Modern amplifiers employ a number of stages of amplification, the signal being fed

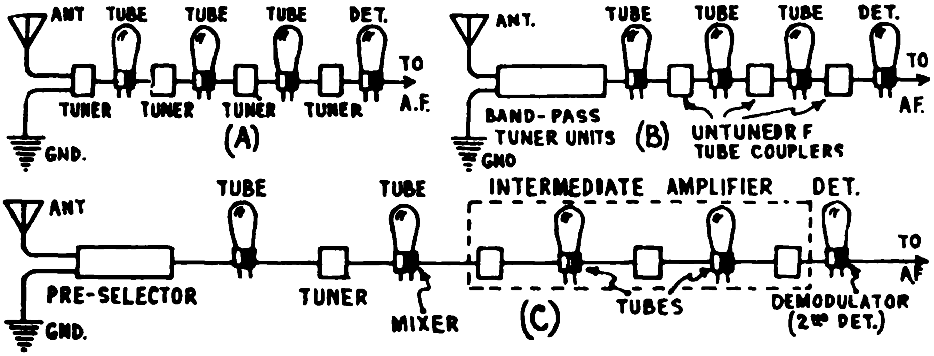


Fig. 245—(A)—T-R-F receiver system. (B) Band selector system. (C) Superheterodyne system.

to the grid circuit of the first tube. The output voltages appearing across the load in the plate circuit of this tube are fed to the grid circuit of the next tube, etc. It is not at all uncommon to use 5 or more high-gain stages of amplification ahead of the detector. The problem of tuning can of course be solved by using as many resonant circuits as are necessary to reduce the strength of the signal-voltage variations of the unwanted stations down to a value where they do not cause interference with those of the station being received. The degree of selectivity required for this purpose depends both on the signal strength of the stations it is desired to receive and that of the unwanted stations whose fields affect the receiving antenna simultaneously.

There are several arrangements possible with the amplifying tubes and tuned circuits in the r-f amplifier. As shown at (A) of Fig. 245, we may select and amplify in successive steps by following each tuned circuit by an amplifier tube. This is the common method used in tuned radio-frequency ("t-r-f") amplifiers. The overall response of the several tuned circuits to frequencies off resonance is diminished, in a logarithmic function. That is, if a single stage delivers 5 times as much voltage at the frequency of resonance as it does at some other frequency, the total discrimination in favor of a desired signal is 5×5 or 25 in a 2 stage amplifier, or 5^N if there are N stages.

In another type of receiver, the selectivity and amplification are accomplished separately as shown at (B). Either the selection is accomplished first by means of a series of tuned circuits usually in the form of a "band-pass" tuner, and the output voltage is then amplified by a vacuum tube amplifier which amplifies signals of all frequencies the same amount; or else, the amplification is accomplished first and then selection by tuned circuits follows. The former method is best of course because it is relatively easier to suppress the unwanted signals as soon as they are received than it is to suppress them after they have been amplified by the amplifier along with the

wanted signals. The selector in the former system is commonly known as the "band-pass tuner" or "band selector" because it selects or passes a band of frequencies 10 kc wide.

In the superheterodyne system of reception which has become exceedingly popular, the incoming signal is first selected partially in the pre-selector or r-f amplifier, then the frequency of the signal is changed to a lower frequency (which can be more efficiently amplified), and is then amplified at this intermediate frequency by the "intermediate-frequency" amplifier. It is then demodulated by the so-called "second detector", as shown at (C). A certain amount of selectivity is also obtained in the frequency-changing process. We will study the tuned radio-frequency, and "band selector" systems first, reserving the superheterodyne receiver for later detailed study in Chapter 22.

In spite of all the changes which have taken place in radio receiver design, there has been very little change in the fundamental principles involved in amplifier design, although certain new principles have been added and the constants of most circuits have been revised to suit the newer types of vacuum tubes. Of course the mechanical construction of the parts have been continually changed in order to reduce the cost of raw materials necessary, greatly simplify and cheapen the manufacturing processes, and reduce the overall dimensions of the entire receiver.

350. Tuned radio-frequency amplification: A single stage of *tuned radio-frequency* (hereafter abbreviated t-r-f) amplification shown at the left of Fig. 246 is connected ahead of a grid leak-condenser detector to form the circuit shown at the right. The circuit is that for a simple battery-operated receiver, but of course the same general arrangement could be employed for a-c operated tubes (with proper filament and plate voltage supply) or for a screen-grid type of r-f amplifier. We are concerned mainly with the simple t-r-f type of circuit at this time; later we will study several variations of it with different types of tubes, etc. The r-f transformer T has been added to the detector. As we have already considered the detailed theory of the tuned circuit and r-f transformer in Articles 245 to 250, we will not repeat this. Also, the action of the vacuum tube as an amplifier and detector was studied in detail in Chapter 20 (from Art. 336,—on), so this will not be repeated again. (The reader is advised to review this material at this time if necessary, in order to better understand the work which is to follow.)

To add a stage of t-r-f amplification to the detector, it is only necessary to couple the antenna circuit to the grid circuit of the amplifier tube by some device, such as an r-f transformer, and to couple the output or plate circuit of the r-f amplifier tube to the input or grid circuit of the detector tube. If the transformers are used for coupling, this means connecting the primary of the first transformer into the antenna circuit, and the secondary in the grid circuit of the amplifier tube. The secondary of each transformer is tuned by means of the variable tuning condenser as shown, to form a series resonant circuit. We will now proceed with the explanation of the operation of this simple t-r-f circuit of Fig. 246:

Very weak r-f voltages are induced in the antenna by the passing radiations sent out by the broadcasting stations. The induced voltages cause currents of corresponding frequencies to flow up and down the antenna circuit between the antenna and ground (since the antenna circuit is really a condenser circuit, see Fig. 177 & 179). The

antenna circuit contains a number of these signal currents received simultaneously from various stations, and all having different frequencies. These currents, flowing through the primary coil of the first transformer, produce magnetic fields which link and unlink with the secondary coil and induce potentials of corresponding frequencies in it. This coil and its associated tuning condenser form a resonant circuit, the resonant frequency of which is determined by the inductance of the coil and the capacity setting of the condenser. The impedance or opposition to the flow of current of this frequency is very small, while the opposition to the flow of currents of all other frequencies is high. Therefore, the induced potential across its secondary which is of this resonant frequency, is able to send an appreciable amount of current at this frequency through the tuned circuit. This current causes corresponding voltage variations between the ends of the secondary or between the grid and filament of the amplifying tube. The varying plate current of the tube flows through the primary of the coupling transformer T. This current is a *pulsating direct current* (because the plate current of a vacuum tube can only flow from plate to filament or cathode), having pulsations occurring at the frequency of the signal being received and varying in strength according to the modulation. The flow of this pulsating current through the primary of transformer T produces a magnetic field which induces an alternating voltage in the secondary, of the same frequency as the potential across the grid of the first tube, but of a greater amplitude. The steady flow of the "B" battery current through the primary to the plate has no inducing effect in the transformer, but as soon as it becomes interrupted or varied due to the signal, the magnetic field varies accordingly, and an r-f voltage is induced in the secondary. (This is in accordance with the well known laws of

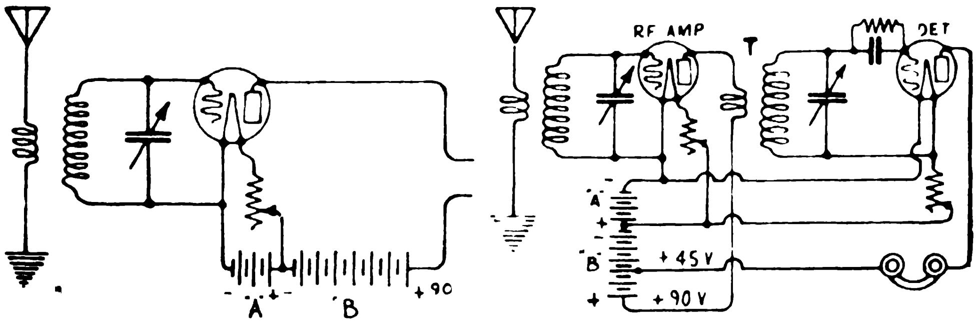


Fig 246—Left: Single stage of t-r-f amplification
Right. Single stage of t-r-f and detector with common filament and plate voltage supplies

electromagnetic induction.) This voltage acts between the grid leak and condenser terminal, and the filament of the detector tube, producing a pulsating direct current varying at the audio or modulation frequency in the plate circuit and the phones, where the amplified signal is reproduced in the form of sound waves.

The real use of the coupling transformer "T", then, is to obtain an alternating voltage of radio-frequency across the grid circuit of a tube, from the pulsating plate current of the preceding tube. Obviously the higher this input voltage to the grid circuit of the second can be made, for a given value of pulsating current in the plate of the first tube, the more efficient the coupling and the louder will be the signals. Usually the transformer is made to give a step-up in voltage by having a greater number of secondary turns than primary turns, although there are other factors which affect this. Also it is evident that the larger is the impedance of the primary winding of this transformer, the greater will be the amplification obtained from the r-f amplifier tube, since this primary forms the plate circuit load for the tube (see Article 337). The use of the tuned

circuits results in additional gain due to the stronger voltage variations set up across the tuned circuit by the current flowing through it at resonance.

The filaments of the two tubes are connected in parallel across the common A-battery with variable rheostats for adjusting the filament current. The plate circuits are also connected in parallel across the common "B" battery, 45 volts being applied to the plate of the detector and 90 volts to that of the r-f amplifier tube.

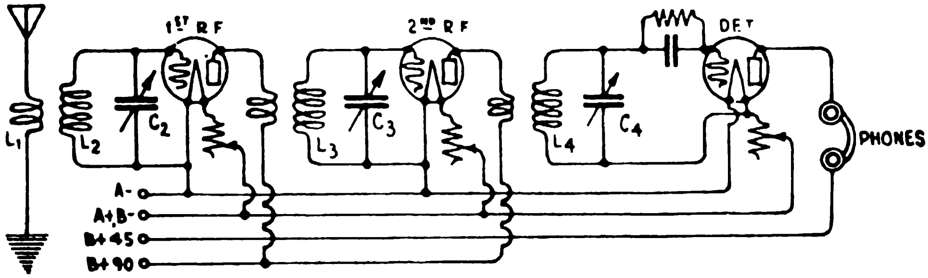


Fig 247—2 stages of tuned radio-frequency amplification and detector

351. Multiple tuned r-f: Since a single r-f amplifier stage would hardly provide sufficient selectivity or amplification for satisfactory reception, more similar stages may be added to it. An additional stage connected to it is shown in Fig. 247. Theoretically, any number of amplifier stages (an amplifier stage consists of the amplifier tube together with its coupling device), could be added, but in practice, the number is determined by the total amplification desired, the amplification produced by each tube and coupling device, and in many cases the selectivity desired, since this determines the number of tuned circuits to be employed. The simple five tube t-r-f receiver, popular for several years, employed two stages of r-f amplification, detector, and two stages of audio amplification.

352. Resistance-coupled r-f amplifier: The successive amplifier tubes in radio frequency amplifier stages can be coupled by resistances as shown in Fig. 248. Here the variation of the plate current in the plate resistor R_1 produces across it a varying voltage drop which actuates the grid of the next amplifying tube. It is necessary to introduce blocking condensers "C" to prevent the high plate voltage of each tube from being impressed directly on the grid of the following tube. The grid circuit is returned through the grid resistor R_2 to the negative side of the filament or to the negative terminal of a C-battery for proper grid-bias voltage.

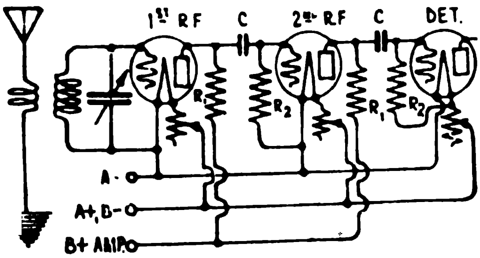


Fig. 248—2 stage resistance-coupled r-f amplifier and detector.

The relationship between voltage and current is independent of frequency for a pure resistance, and therefore in the case of resistance amplification with a three-electrode tube the voltage amplification obtained would be the same for all frequencies if there were really no capacity or inductance anywhere in the plate circuit. But although the series resistance R_1 may be made sufficiently free from inductance and capacity to ensure practically constant impedance over the range of frequencies likely to be encountered in practice, a comparatively large amount of capacity does exist between the plate and cathode of the tube itself; the plate and cathode constitute the two plates of a "small" condenser as shown in Fig. 224 and Fig. 249.

Now, although no direct current will flow through a circuit having a condenser in series, alternating current can, and therefore a fraction of the pulsating plate current of the tube will flow in and out of the plates formed by this capacitance (the plate and the cathode) instead of all passing through the coupling resistance R_1. Since the amplified voltage developed across R_1 is proportional to the variations in current through it, it follows that this by-passing of some of the current through the plate to cathode (or filament) capacitance will result in the pulsating voltage across R_1 being less than

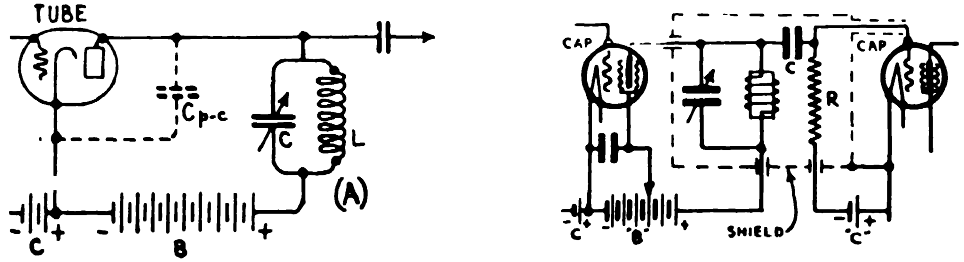


Fig 249—Left: How the plate-cathode capacitance of the amplifier tube acts as a shunt capacitance across the plate load
Right: Tuned plate impedance coupling for r-f amplifier

if no capacitance were present, and the efficiency of the arrangement as an amplifier is impaired for radio-frequency signals. The grid-cathode capacitance also shunts grid resistor R_2.

The loss of amplification due to the inter-electrode capacitance of the tubes does not become serious until the amplifier is used to amplify radio frequencies, since the reactance of this capacitance is rather high at the low frequencies, and hence it does not act so much as a shunt. For this reason, this type of amplifier is generally unsatisfactory for use as an r-f- amplifier for short wave or broadcast band reception because of the high frequency and the large shunting effect of the plate-cathode capacitance. Resistance-coupled amplifiers give good results on long-wave reception at around 300,000 cycles (1,000 meters) or less. At these comparatively low frequencies the tube capacitances do not have such a great effect. However, all of the amplification in a resistance coupled amplifier is derived from the tubes themselves, no voltage step-up being obtained from the coupling device. This makes it necessary to employ a larger number of tubes for a given amount of amplification than when transformer coupling is used. Under modern broadcasting conditions, more than one tuned circuit would have to be used in an amplifier of this type in order to obtain the required selectivity. The resistance-coupled amplifier is especially useful where it is desired to amplify signals over a very wide range of frequencies without changing any of the apparatus in the circuits. For instance, an amplifier of this type can be designed to amplify signals from about 1,000 meters to 20,000 meters without changing the parts in any way.

As we shall see later when discussing audio amplifiers, resistance coupling lends itself to audio-frequency amplification, because by proper design of the amplifier the degree of amplification obtained can be made practically uniform over the whole of the range of audible frequencies, a desirable condition for high-quality reproduction from a receiver. It is for this reason that audio amplifiers in television receivers are almost

entirely of the resistance-coupled type since they must amplify a very wide range of audio frequencies. The resistance-coupled a-f amplifier will be studied in detail in Articles 432 and 433.

Note: Another objection to the resistance-coupled amplifier is that in order to actually obtain a large proportion of the amplification factor of the amplifier tube, the plate coupling resistor R_1 must be of large value, (see (F) of Fig. 242). For instance, if the coupling resistor equals the a-c plate resistance of the tube, only half the mu of the tube is obtained. If this resistor is made of high resistance, the voltage drop ($I_p \times R_1$) due to the plate current flowing through it will be large, with the result that the voltage actually effective at the plate will be materially reduced. Of course, one remedy for this is to employ a B voltage supply device which will apply higher voltage to the circuit, but the cost of such devices increases very greatly as their voltage rating increases. As a compromise between these conflicting conditions, resistance amplifiers are usually designed with a plate load resistance R_1 of at least 3 to 5 times the a-c plate resistance of the tube, together with a B voltage supply at least equal to the maximum permissible *actual* plate voltage given in the manufacturer's rating of the tube.

353. Plate-impedance r-f coupling: Since the object is to connect as high an impedance as possible in the plate circuit of an amplifier tube in order to realize a large proportion of the tube's amplification factor, it has been thought at times that a coil having a rather low resistance and large inductance could be used in place of the resistance in the amplifier described above. This arrangement would be called *plate impedance coupling.*

A coil having a large inductance has a high impedance at high frequencies, and if it is constructed so its ohmic resistance is fairly low, the voltage drop across it due to the *steady plate current* flowing through it would not be very great, and normal B voltages could be used. Since it has a high impedance, any variations in the plate current flowing through it, due to an incoming signal, would produce large inductive voltage variations across it, and these would be communicated to the grid of the next r-f tube. Here, as in the case of the resistance coupled amplifier, the plate-cathode and grid-cathode capacitances (see (A) of Fig. 249) become the factors limiting the possible amplification, due to partial by-passing of the *varying* plate current which would otherwise all flow through the plate impedance and produce useful voltage variations across it. In addition, the distributed-capacity existing between the individual turns of the coil also acts as a by-pass. The amplification will be reduced at all frequencies except the one at which the coil and the total coupled stray capacitance across it are resonant. At this particular frequency, a parallel resonance circuit forms, and since such a circuit presents a very high impedance to flow of currents of the resonance frequency through it, the tube is working into a high impedance at this one frequency and high amplification is produced.

This suggests the use of an arrangement whereby a parallel variably-tuned circuit may actually be connected in the plate circuit and tuned to whatever frequency it is desired to receive. This is practical and will now be described. An impedance may be used when this type of amplifier is used for audio-frequency amplification as we shall see.

354. Tuned-plate impedance r-f coupling: The arrangement for a typical amplifier stage with tuned-plate impedance coupling is shown at (A) of Fig. 249.

Here the inductance coil L is tuned to parallel resonance, at the particular frequency of the signal it is desired to receive, by means of the variable tuning condenser C. The tuned circuit offers a high impedance to the flow of current of the frequency of resonance through it, and so acts as a high impedance load in the plate circuit of the tube at this frequency. Under this condition good amplification may be secured. When it is desired to receive the signals of another station broadcasting on a different fre-

quency, the variable tuning condenser is adjusted to bring the circuit to resonance at this frequency and so on. Thus, maximum amplification is produced for the frequency to which the tuned circuit is resonant. Of course the tube amplifies all other signals as well, to a degree depending upon the impedance which this parallel circuit offers at this frequency. It is therefore necessary that this circuit tune sharply in order to obtain good selectivity, so that its impedance to the frequencies of all unwanted signals will be much lower than that to the frequency of the wanted station and therefore the amplification of the tube at these other frequencies will be low.

Actually, the condenser C is not the only capacitance across the tuning inductance L. Another small condenser C_{pc}, (shown dotted), due to the capacitance between the plate and cathode of the tube is actually shunted across the coil. It will be remembered that this is the condenser which caused the shunting action across the load in both the resistance and impedance-coupling circuit schemes. Since this capacitance is now really in parallel with the tuning condenser D, it means that the exact capacity setting of C necessary to tune Coil L to resonance at a given frequency, is really slightly less than the formulas for resonance indicate, by an amount equal to this plate-cathode capacitance.

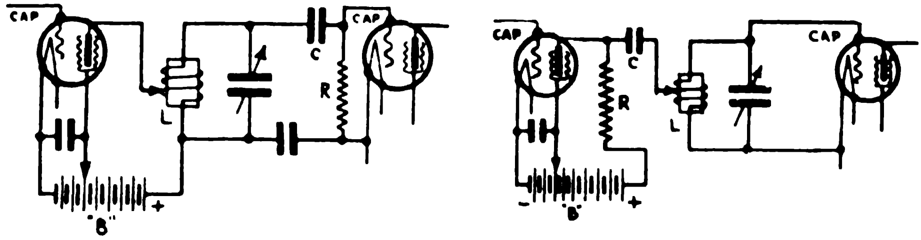


Fig 250—Left: Plate-autoformer coupling in an r-f amplifier
Right: Grid-autoformer coupling with parallel-feed plate supply

Since fairly low resistance radio-frequency inductance coils are easily constructed, and since the effective impedance of a parallel tuned circuit may be made very high at resonance, by using a large inductance of low ohmic resistance value (effective values as high as 100,000 ohms or so are rather easy to attain), fairly good amplification may be obtained by this arrangement. However, the selectivity is rather poor due to the fact that the plate resistance of the tube is really shunted across the tuned plate circuit (if we consider the circuit from the point of view of the latter), thus lowering the effective impedance. Tuned plate coupling is especially advantageous when screen grid tubes are employed as the r-f amplifiers, because since screen grid tubes have rather high a-c plate resistances (400,000 ohms for a '24 type screen-grid tube as compared to only 9,000 ohms for a '27 type tube) it is necessary to use a plate circuit load of high effective impedance if much amplification is to be obtained. The use of a parallel tuned circuit is one of the most convenient ways of obtaining this high impedance. A typical tuned-plate circuit r-f amplifier stage with screen-grid tubes is shown at the right of Fig. 249. From the end of the impedance leading to the plate of the tube, a lead runs to a blocking condenser C, the other side of which is connected to the grid of the following tube. The variations in voltage across the impedance cause electron flows which are communicated around through the B battery circuit and grid leak resistor R to the other plate of the blocking condenser and the grid. The blocking condenser serves the purpose of preventing the high direct positive plate voltage of the first tube from being impressed directly on the grid of the following tube, as it would if the top of the tuned circuit were connected directly to the grid of the second tube. This condenser may be of about .001 mfd. capacitance for an r-f amplifier.

A serious disadvantage of this method of coupling is that there is a strong tendency to oscillate, due to feedback through the grid-plate capacity of the vacuum tube when the plate circuit is tuned to resonance (unless screen-grid tubes with their very small grid-plate capacity are employed). This tendency is especially strong in multi-stage amplifiers. It can be

reduced by various stabilizing methods, but these reduce the obtainable amplification. However, this type of coupling can be used to good advantage with screen-grid tubes. Also, all of the amplification is produced by the tube itself, no step-up in voltage being produced in the coupling circuit between successive tubes as is the case with properly designed coupling transformers, where there may be a step-up in voltage from the primary to the secondary. Another disadvantage is that as the movable condenser plates are at +B potential (since they conneet to the positive terminal of the B voltage supply) the rotor plates and condenser frame must be insulated carefully from the grounded metal shielding usually employed in this type of amplifier This can be taken care of, but it complicates the set construction somewhat.

355. Auto-transformer coupling: In the straight tuned-plate impedance coupling shown in Fig. 249 the tuning is rather broad, even when good tuning coils having low ohmic resistance are employed. If, however, the coil and condenser are connected as shown at the left of Fig. 250, the selectivity will be greater: The tuning coil really acts as an auto-transformer now:

The plate current of the tube flows up from the lower end and out of the tap to the plate. This part of the winding is therefore the primary of the transformer. The varying plate current flowing through this, induces a higher voltage in the secondary which consists of the entire coil. The primary and secondary voltages will be 180 degrees out of phase, in accordance with the theory of ordinary transformer action. The inductive coupling between the primary and secondary parts of the winding (for the same number of primary turns) is greater in this type of coil than in one having a separate primary and secondary, hence a greater plate circuit impedance is built up with a relatively small number of turns, resulting in greater overall amplification. The selectivity of this arrangement is good, but the fact that the tuning condenser plates are at the high B+ potential is a disadvantage. This is known as *plate auto-transformer coupling* In the grid *auto-transformer* coupled circuit shown at the right, this disadvantage is removed by connecting the auto-transformer L with its tuned secondary in the grid circuit and coupling it to the plate circuit by a high resistance R and a coupling condenser C of about 001 mfd. or so. The position of the tap on the tuning coil determines what proportion of the entire coil acts as the primary, and therefore this affects the voltage step-up in the coil. However, the fewer the number of turns included between the bottom and the tap, as the primary, the smaller is the impedance being placed in the plate circuit of the tube and therefore the less is the amplification derived from the tube. Consequently, if the tap were moved down step by step, the selectivity would increase as the number of turns actually included in the plate circuit were reduced. A point is reached however, where further lowering of the tap produces considerable overall decrease in amplification.

356. Parallel-feed plate supply: In the circuits shown in Figs. 246, 247, 249 and the left of Fig. 250, the direct plate current of the tube flows directly through the tuning coil. In the circuit at the right of Fig. 250, this current flows through the resistor R. So far as any steady direct plate current flow through R is concerned, it has no effect on the coil. However, when any variation in the plate current occurs due to a signal, the variation in voltage drop through the resistor is communicated to the coil circuit by means of the blocking condenser C. This connection is known as *parallel-feed* plate supply, because the direct plate current does not flow through the coupling unit, but rather through a separate parallel circuit employed for that purpose.

A choke coil having low distributed capacity is usually employed in place of resistor R in practice, so that the voltage drop due to the passage of the steady plate current is not excessive. Parallel-feed plate supply can also be used in transformer-coupled audio amplifiers, as we shall see later, in order to eliminate the effects of core saturation which might be caused by the steady direct plate current flowing through the primary of the transformer. At (A) of Fig. 251 the use of an r-f choke coil (an inductance of about 85 millihenries) for parallel-feed in an auto-transformer coupled r-f stage is shown; and the arrangement in a transformer-coupled audio amplifier stage is shown at (C). A larger size of coupling condenser and choke coil is needed in the case of audio amplifiers, as shown, on account of the lower frequency The coupling condenser is usually of .25 mfd., and the choke of 30 henries inductance. For a radio-frequency amplifier, a choke of 85 millihenries is usually employed with a coupling condenser of from .001 to about 005 mfd.

357. Selectivity of multiple stages: The selectivity (measure of the ability of a receiver to suppress the signal impulses of all unwanted stations) of a radio frequency amplifier depends on the number of tuned stages, and the selectivity of each stage. The first factor is illustrated at the left of Fig. 252.

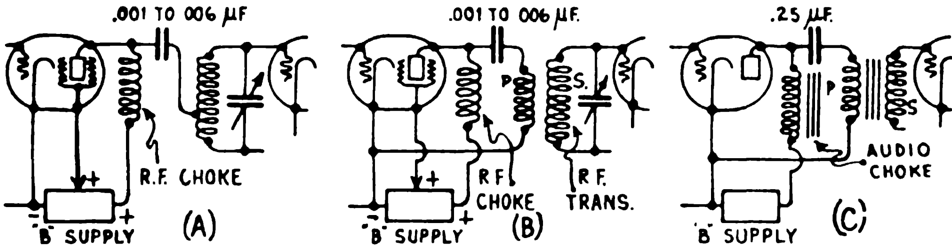


Fig 251—Parallel-feed plate supply systems (A) and (B) for an r-f amplifier, (C) for an audio amplifier

Let curve A represent the response curve of a single tuned r-f stage, that is, the height of the curve at any point represents the "per cent of the amplification at resonance" which is obtained at the frequency corresponding to that point. The receiver is supposed to be tuned to resonance at 600 kc. Then, a signal having a frequency 5 kc off resonance (above or below the frequency of resonance), is amplified about 90 per cent as much as one of the resonance frequency,—which is taken as 100 per cent. A signal having a frequency 10 kc off resonance is amplified only 81 per cent as much as the signal to which the circuit is tuned, etc. Now if another stage with characteristics exactly identical to the first is added to it, the selective action shown by curve B is obtained. This can be understood from the fact that if for a signal of a certain frequency off resonance the first tuned circuit reduced the strength to 90 per cent, then the second tuned circuit would reduce the strength to 90 per cent of what came through the first stage, i.e., 90 per cent $\times$ 90 per cent, or 81 per cent. A third tuned stage would reduce it to 81 per cent $\times$ 90 per cent, or 73 per cent. A fourth tuned stage would make it 73 per cent $\times$ 90 per cent, or 66 per cent, etc. Reference to the curves at a point 5 kc off resonance, shows the selective action referred to above. Under these conditions of selectivity, a signal voltage whose frequency is 5 kc off resonance, is only amplified 66 per cent as much as that of a signal of the frequency to which the circuits are tuned.

The illustration at the right of Fig. 252 shows in a pictorial way how the signal strength is increased and the width of the frequency band passed through is decreased, as the number of tuned r-f stages are increased. Starting at the antenna circuit at the left, the undesired signals are reduced somewhat by the first tuned circuit, then all signals are ampli-

fied by the vacuum tube to a greater strength (as shown by the higher curves), then the next tuned circuit further reduces the strength of the undesired signals, etc. It is obvious that the tuning of each stage must be designed to be broader than that desired from the amplifier as a whole, due to the successive reducing action of the various tuned circuits. It should be remembered that the selectivity is gained entirely by means of the tuned circuits, none whatever is obtained from the vacuum tube, because a vacuum tube will amplify without discrimination, voltages of any frequency applied to its grid circuit. It is evident, then that in ordinary tuned r-f amplifiers, sharp tuning may be obtained by employing a number of tuned stages and amplification is obtained by using a number of amplifier tubes. Under present broadcasting conditions with powerful stations,

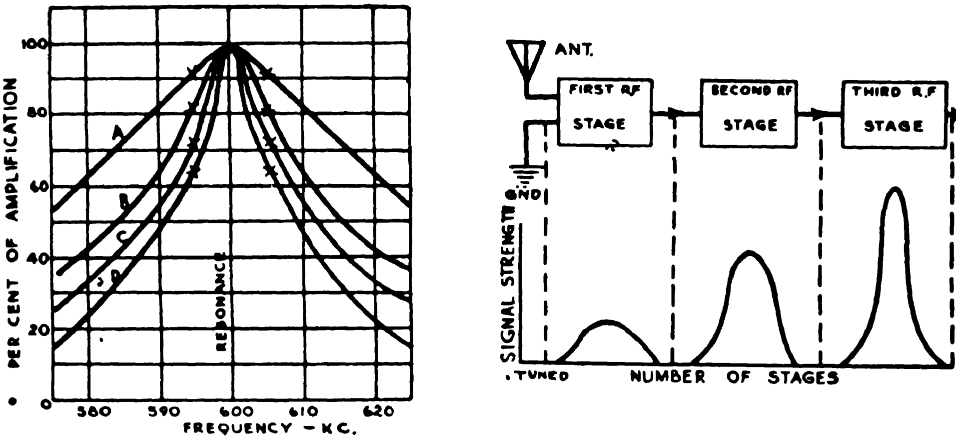


Fig 252—Left Why several tuned circuits in cascade increase the selectivity by successively reducing the strength of the unwanted signals
Right Pictorial representation of how several tuned stages amplify, and sharpen the tuning

a single tuned circuit is unable to sufficiently weaken the signals of undesired local stations to make them inaudible. In practice, a number of such stages must be used to obtain the necessary selectivity to be able to completely eliminate the signals of all other stations when listening to any one station.

358. Desirable shape of tuning curve: It would seem from this discussion that it is very desirable to obtain an overall tuning curve which is very narrow and steep, somewhat as shown by curve A at the left of Fig. 253. A tuning characteristic like this would mean that only the signal currents of the station transmitting with a carrier frequency equal to that to which the tuning circuits were tuned, would be allowed to pass through the amplifier freely, the signals of stations of all other frequencies would be very greatly reduced in strength by the high impedance offered to their flow by the series tuned circuits. Actually, a tuning curve as sharp and peaked as this is undesirable from the standpoint of good audio-frequency reproduction as we shall see.

In order to obtain a sharp tuning characteristic like that of curve A, the tuned circuits must have low a-c resistance. The a-c resistance of a good isolated tuned circuit can be made as low as 10 or 12 ohms at a frequency of 1,500 kc. (200 meters wavelength). However, its resistance when placed in an actual receiver depends largely upon what circuit and objects are brought near its magnetic field. The associated circuits may consist of coupled primaries, and the input circuits of vacuum tubes which are connected directly across the tuned circuits. The mechanical things include metal end-plates of condensers, shielding, etc. From the standpoint of signal strength and selectivity alone, all these factors should be controlled so that a low resistance results in the tuned circuits. However, the resistance can be made so low, and the tuned circuits made to tune so sharp, that an undesirable effect is produced. This is known as *cutting sidebands.* Curve A of Fig. 253 has purposely been drawn very sharp to illustrate this condition. The frequency of resonance is assumed as 600 kc.

Consider that a musical selection is being played in a station transmitting at 600 k. c. (500 meters), and that the signals of this station are

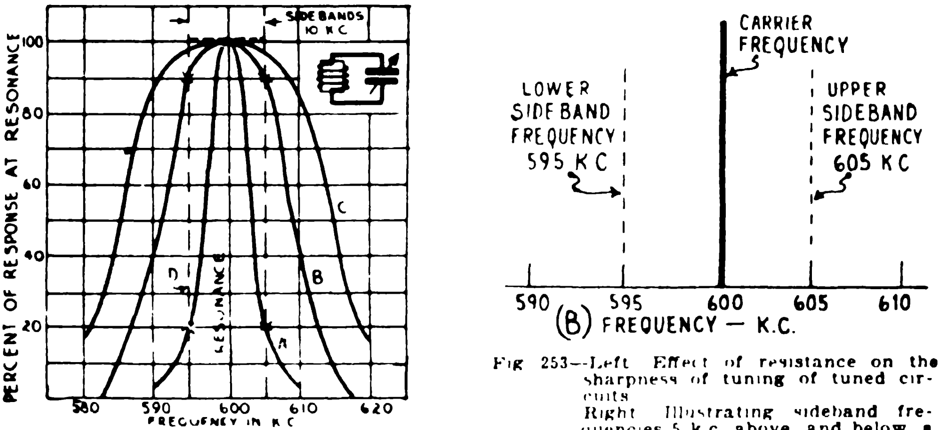


Fig 253—Left Effect of resistance on the sharpness of tuning of tuned circuits
Right Illustrating sideband frequencies 5 k c above, and below, a carrier frequency of 600 k c

being picked up at the receiving station and are impressed on the tuned circuit whose characteristic is represented by curve A at the left of Fig. 253. Although many of the larger broadcasting stations are equipped to transmit all audio frequencies up to 10,000 cycles, the fact that most radio receiving equipment in general use at the present time is not able to reproduce sounds above 5,000 or 6,000 cycles, and also the fact that many stations located in the same vicinity are assigned to transmit with carrier frequencies only 10 kc different from each other, has resulted in their transmitting only those sounds between about 40 and about 5,000 or 6,000 cycles. We will consider for our discussion that the upper limit is 5,000 cycles.

Therefore at the broadcasting station considered, the 600,000-cycle carrier current wave is modulated by the audio-frequency currents ranging from 40 to 5,000 cycles. Consider first that only a 5,000-cycle note is being played by the orchestra. This 5,000-cycle audio current then combines with the 600,000-cycle carrier current producing two additional currents, one having a frequency equal to the "sum" of these two (605,000 cycles), and one having a frequency equal to the "difference" of these two (595,000 cyles), see (B) of Fig. 253, and Arts. 383 & 384 Therefore, to receive this note, the r-f amplifier must pass these two currents through it with equal strength. You will notice that they differ in frequency by 10,000 cycles, or 10 kilocycles. Now if a 3,000-cycle note

is played, the carrier wave will contain a 603,000-cycle note and a 597,000-cycle note and the amplifier will have to amplify these equally. It can be seen that if the entire range of musical frequencies is being covered at once by the orchestra there will be present a carrier wave covering a *band* of frequencies from 605,000 cycles to 595,000 cycles, and in order to secure faithful reproduction at the receiver, *every one* of these frequencies must be *passed through the r-f amplifier and amplified equally*. If any frequency is suppressed in the amplifier, then that note will not be reproduced in the loudspeaker, and the music will not be a true reproduction of that played in the broadcast studio. This condition would occur if the frequency response of any one tuned circuit or of the entire r-f amplifier were as shown by curve A. All the frequencies to 5 kilocycles above the carrier and the 5 kilocycles below the carrier (10 kc. altogether) constitute what are known as the "*sidebands.*"

It is evident that in this case the response for the 595 and 605 kc. sidebands (5,000 cycle audio note) is only 20 per cent as large as the response of sidebands near the resonance frequency. Therefore this high 5,000-cycle note would be heard very weakly, if at all, in the loudspeaker. Other notes lower than this would be suppressed in varying degrees as shown. This frequency response is evidently too sharp for good audio quality reproduction.

Tuning characteristics represented by curve B would be more nearly ideal, since the response at 595 kc. is 90 per cent of the response at resonance. Curve C is obviously a further improvement in this respect. However, curves B and C indicate broad tuning with poor selectivity and consequent danger of station interference. It can be seen that with this type of tuned circuit some compromise must be effected. Some compensation for the loss of the high frequency notes due to cutting of side bands by over-selective tuning circuits can be secured in the audio amplifier and reproduced by designing this to have a rising characteristic at the high frequencies. This means selecting the audio and reproducer units to match the operating characteristics of the r-f amplifying system.

Obviously the ideal response curve would be that shown by the dotted lines at D. This tuning curve has straight vertical sides, a flat top, and is 10 kc. wide. Since the peak of the wave is no greater at the carrier frequency than at 5 kc. above or below the carrier, equal transmission is obtained on all frequencies within the 10 kc side-band range.

Frequency response, or tuning curves, approaching this can be obtained in several ways by means of band-pass filters, coupled circuits, or the special Vreeland and Hopkins circuits which will be described. The actual existance of the sideband frequencies mentioned above has been questioned by many authorities since from the physical point of view, the modulation which takes place in the broadcasting station is *amplitude modulation* of the carrier current. However, whether we fully accept the idea of the existance of the sidebands or not, the fact remains that it helps considerably in explaining some phases of tuning circuits. At any rate, the fact that circuits which tune too sharply will suppress the high-frequency audio notes issuing from the loud speaker, can be demonstrated experimentally, so the facts remains that the tuning circuits should not be made too selective if good tone quality is to be preserved. We will now proceed to a study of several circuit arrangements which are employed to obtain a tuning curve which approaches the steep-sided flat-topped curve of D.

It is interesting to note that strictly speaking, the ordinary simple tuned circuit is really a band-pass filter passing a rather limited band of frequencies. The broader is the tuning of such a circuit, due to resistance, etc., the wider is the band passed, as will be seen from curves B and C at the left of Fig. 253. The objection to this form of circuit is of course that if it is made to tune broadly enough to pass a band of 10 kc. without reduction in strength, it will also pass many more frequencies above and below this (see curve C) because the sides of its tuning curve are not straight. What we desire is a tuning circuit able to transmit without reduction a band of frequencies

about 10 kc. wide, and to sharply cut off all frequencies above and below the band, as shown by curve D.

359. Hopkins band rejector system: In the Hopkins band rejector circuit arrangement, a band-pass effect (see Article 187) is obtained and all frequencies above and below the band are suppressed or rejected. This circuit is particularly adapted for use with screen-grid amplifier tubes because it places a high impedance load in the plate circuit of the amplifier tubes. A description of this circuit, developed by Mr. Charles L. Hopkins, follows:

"The Hopkins circuit is actually an impedance-coupled amplifier in which the impedance of the output circuit of one tube is common to that of the input circuit of the succeeding tube. Of course, one object of the amplifier is to produce as much increase in the voltage impressed upon the grids of successive tubes as possible, and in order to do this it is necessary that the voltage drop across the elements of the external plate circuit be as great as is consistent with stable operation.

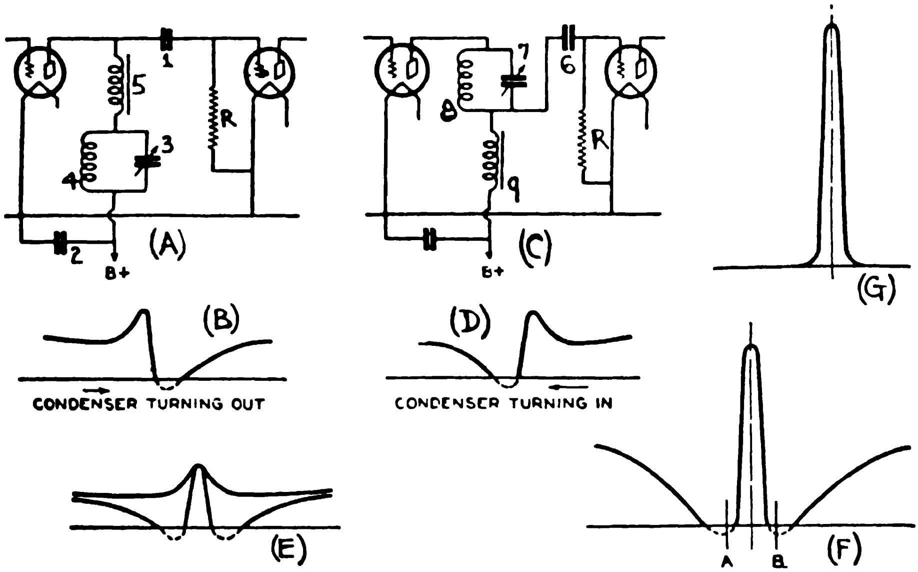


Fig. 254—Hopkins band rejector system. With the circuit at (A), the tuning response at (B) is obtained. With the circuit at (C), the tuning response at (D) is obtained. This is the exact opposite of (B).

With screen-grid tubes the high plate resistance makes it necessary to greatly increase the impedance of the external plate circuit, over that necessary with the -27 type, in order to create a high voltage drop for impression upon the grid of the following tube. A parallel resonant circuit, of the type sometimes called a wave-trap, is employed as the best means for supplying the high impedance, in spite of the fact that such a system, as usually employed, presents problems due to the tendency of such circuits to oscillate and become decidedly unstable when as many as three stages are used.

A form of coupling means which may be used in the Hopkins system is shown at A of Fig. 254. The plate circuit is seen to consist of a combination of a choke coil in series with a parallel tuned circuit, with the plate return through these impedance elements and a fixed condenser. The fixed condenser, 1, between the plate of the first tube and the grid of the second, is for the sole purpose of isolating the grid from high plate voltage. A leak, R, is provided to prevent blocking of the second tube. The choke coil, designated as 5 in the diagram, is so designed that it has a large value of inductance with a very small distributed capacity. At the same time the capacity is sufficient to

tune the circuit to a frequency much lower than the frequency used in the amplifier, so that the choke acts as a capacitive reactance to this frequency, and functions as a very small condenser; that is, a condenser having high capacitive reactance.

Two fundamental electrical laws enter into the analysis of the working of this system. The first is that when a capacity and an inductance are in series and the reactances are mutually balanced (circuit is in resonance) at some particular frequency, the current at that frequency meets with no impedance other than the ohmic resistance of the circuit, and consequently no voltage drop will occur across them. The second law is that when a circuit, such as that incorporated in inductance 4, and condenser 3, is brought into parallel resonance at a certain frequency, there is no reactive impedance at that frequency, but the ohmic resistance is extremely high.

Now, if the trap circuit comprising the inductance 4, and capacity 3, is tuned slightly higher than the frequency of the radio signal, the impedance across the circuit becomes highly inductive, and, if it is tuned slightly lower in frequency, the impedance becomes highly capacitive. The combination of elements in the plate circuit, when arranged as shown, therefore offers to the amplifier plate current either inductive reactance, capacitive reactance, or series resonance (no reactance) because of the fact that one of the elements is variable.

Due to the fact that the adjustment may be such that the reactance of the plate circuit cancels out, there will be a frequency at which there is no voltage drop and consequently no voltage swing impressed on the grid of the second tube. In other words, the signal may be shorted out or shunted back to the input of the first tube. Under these circumstances the ohmic resistance of the choke coil, the only remaining coupling impedance, would not be sufficient to afford a voltage drop great enough to pass the signal to the following tube. At the same setting of the tuning element there will be another frequency at which the trap circuit offers extremely high resistive impedance, and the voltage drop across the trap is all impressed on the succeeding grid. The form of the response curve obtained by adjusting the capacity of the tuning condenser is shown at (B). It is evident that the impedance of the plate circuit is very high at the setting that gives the peak in the curve, so that a high voltage amplification is obtained.

It will be seen that with the arrangement of (A) signals of one frequency are passed along to the second tube, while signals of another and higher frequency will be shorted out, or shunted back. There is thus provided a circuit which has a high degree of selectivity on one side of the desired band of frequencies, but, because of the non-symmetrical shape of the curve has a less than normal degree of selectivity on the other side. Therefore, the system must include a circuit to give a means for eliminating stations on the other side of the band.

A circuit arrangement which gives a curve which is the reverse or complement of the curve is shown at (C). Here again we shall consider the tubes as the first and second, although they are actually the second and third tubes of the circuit. Note that the resonant circuit 7-8, and the choke coil 9, are connected as at (A), except that their relative positions are reversed. The lead to the grid of the second tube is taken from the common connection between the trap circuit and the choke, instead of from the plate of the first tube, as in the previous stage. Here it is the voltage drop across the choke, 9, that is impressed on the second tube.

If the adjustment of the trap is such that its reactance is inductive, it is apparent that it will tend to cancel out the capacitive reactance of the choke coil in the same manner as discussed in connection with the circuit of (A), but it is fundamental that when a capacity and an inductance are brought into series resonance for a given frequency, a very great voltage drop occurs across either of these reactance elements.

If the circuit shown at (C) is set up and the condenser is rotated, the signal strength will change in just the same manner as it did in the case of the arrangement shown at (A), except that the steep cut-off occurs on the other side of the "hump". The curve for this second stage is shown at (D). In this case the reason for the drop in the response curve is that the trap circuit 7-8 blocks or rejects signals of the frequency to which it is tuned. The parallel tuned circuit, instead of being in a path which is common to the plate circuit and the grid circuit, is in but one of these circuits, and it, therefore, prevents the signal current from flowing in the choke. As a consequence of this trapping action there is no current in the common impedance element (the choke) and, therefore, no voltage drop to be impressed on the next tube.

Superimposing the curves shown at (B) and (D), one upon the other, the resulting curve will be as shown at (E). The portion of the spectrum which is transmitted through the tubes is seen to form a comparatively straight-sided, narrow band. The width of the band or channel can be narrowed or widened by adjusting the setting of the condenser, 7. Experiments have shown that the band can be made so narrow that the quality of the reproduction is greatly impaired by side-band trimming, to such an extent, in fact, that a violin can nearly be tuned out due to the narrowness of the band, which will not allow the higher frequencies of the violin to pass through. Therefore, it will be seen that it is readily adjusted so as to obtain ten kilocycle station separation. The shape of the curve of (E) shows that an adjustment for band width of 10 kc. will afford extremely high rejectivity for channels on each side of the desired one. It will also be seen that the top of the curve maintains practically the full band width, which means that the fidelity will not suffer even with great station separating ability.

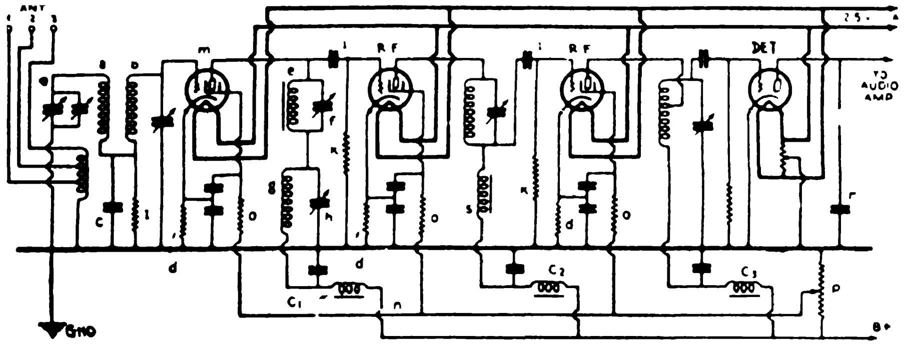


Fig 255—The circuit of a four tube tuner employing three stages of tuned r-f, two of which employ the Hopkins band-pass system described, while the antenna stage makes use of a standard pre-selector circuit

This system for securing station separation may be used in t-r-f receivers and in superheterodyne receivers. It will be understood that in t-r-f sets the condensers which tune the trap circuits are ganged to tune together over the broadcast band, whereas in a superheterodyne, using this system in the i-f stages, these stages are set permanently so as to give the desired band width.

Evidently, when the amplification of the stages is taken into account, the response curve of the two stages combined will be somewhat different from what is shown in the curve at (E). The figure at (F) shows what might be expected from two stages, and it will be seen that the cut-off at each side of the signal becomes steeper as the high part of the curve goes up. The low or no-signal parts of the curve remain fixed at the same distance from the signal frequency, regardless of the amplification or the strength of the signal. This is because the low points A and B are positioned by the wave traps, and these points cannot be moved apart or nearer each other by changes in signal strength.

It will be seen that we have here a means for eliminating undesired signals which are on frequencies close to the frequency of the desired signal, and that strong signals do not broaden the response curve, but merely raise it.

At points on the curve of (F) somewhat distant from the frequency of the desired signal the curve rises to perhaps one-third or one-half of its height at the signal frequency. In the sets which are built using two stages such as shown and described above, one or more additional tuning circuits of the usual types are usually employed When the input to the first tube is tuned in the usual way frequencies somewhat removed from that of the desired signal are "tuned out" ahead of the first tube, while those close to the desired signal are prevented from passing through the receiver by being trapped or rejected in the amplifying stages. In some cases it has been found practical or advisable to employ a band-pass type of tuning ahead of the first tube."

Fig. 255 shows a circuit diagram of the r-f amplifier and detector of a practical receiver employing the Hopkins band rejector system and

using a-c screen-grid tubes in the radio-frequency stages, these tubes being of the indirectly-heated cathode type. In this particular set, there is sufficient amplification ahead of the detector to permit the use of but one audio-frequency stage. In this receiver it will be noted that double tuning is used ahead of the first tube. The two coils *a* and *b* are shielded from each other, the coupling between the two tuned circuits being given by the fixed condenser C which is common to both tuned circuits. A leak resistor is provided across the condenser to prevent blocking of the grid of the tube.

"The grids of the radio-frequency tubes are biased by means of the resistors *d* between the cathode and "B" minus or ground, as usual with heater-type tubes. In the plate circuit of the first tube is located a choke coil *e*, with a small variable condenser *f* connected across it. The purpose of this condenser will be explained later. In series with the choke coil is a trap consisting of coil *g* and condenser *h*. The connection to the grid of the second tube is made through a fixed blocking condenser *i*. The condenser is connected directly to the plate of the first tube. A grid leak *k* is provided because the condenser *i* would otherwise block the grid. The screen grid of the first tube *m* is connected to line *n* through a resistor *o*. The screen grids of the other radio-frequency tubes are also connected through resistors to this line, and a potentiometer p controls the voltage applied to the screen grids and acts as a volume control.

The condenser *f* is usually placed on the shaft of the tuning condensers and thus forms a part of the gang, but if more convenient it may be placed at some point distant from the condenser gang and operated by means of a belt or link movement. This condenser turns in, so as to increase in capacity, as the set is tuned to longer wavelengths. It will be remembered that choke coil *e* acts as a small condenser. It has been found that in order to maintain the shape of the response curve the same at all wavelengths to which the set may be tuned, it is necessary to add extra capacity across the choke as the set is tuned up the scale, that is to say, to longer and longer wavelengths.

Going now to the plate circuit of the second tube, it will be seen that the arrangement is the same as that shown at (C) of Fig. 254. The response curve of this stage by itself would be the same as at (D). The coupling means employed between the third radio-frequency tube and the detector may be the familiar tuned-impedance coupling, or it may be of an untuned impedance type or it may be the usual tuned secondary with untuned primary. The detector and audio amplifier need no explanation, as they may be of conventional types.

(G) shows the overall response curve of the complete receiver. With the input to the detector tuned as shown, the curve tends to become somewhat peaked at the top, but not to such an extent as to noticeably impair the tone quality. As has been pointed out, the system of band-pass tuning as described here is applicable not only to t-r-f receivers but also to superheterodyne construction."

360. The band selector: The purpose of the *band-pass filter* or *band selector* is to present a low impedance to, and allow the passage into a circuit of, currents of a narrow band of frequencies which it is desired to receive; and to offer a high impedance to, and exclude all others, whether higher or lower than the limits of this band. The general theory of ordinary band-pass filters or selectors was explained in Article 187, and formulas for their design were given there, but since the band-pass tuners or filters, employed in t-r-f and superheterodyne receivers differ somewhat in form from these, they will be considered here. We will consider the form used in some t-r-f receivers first.

In the ordinary band selector, two tuned circuits are loosely coupled by means of a small mutual inductance or a rather large mutual capacitance. The elements of the circuit are arranged according to the general circuit

at (A) of Fig. 256. The tuning coil and condenser L_1C_1 are tuned to the same frequency as similar coils and condenser L_2C_2. M is the mutual coupling reactance, which in this case is a small coil, but as we shall see later this may be a condenser, or simply magnetic coupling between the

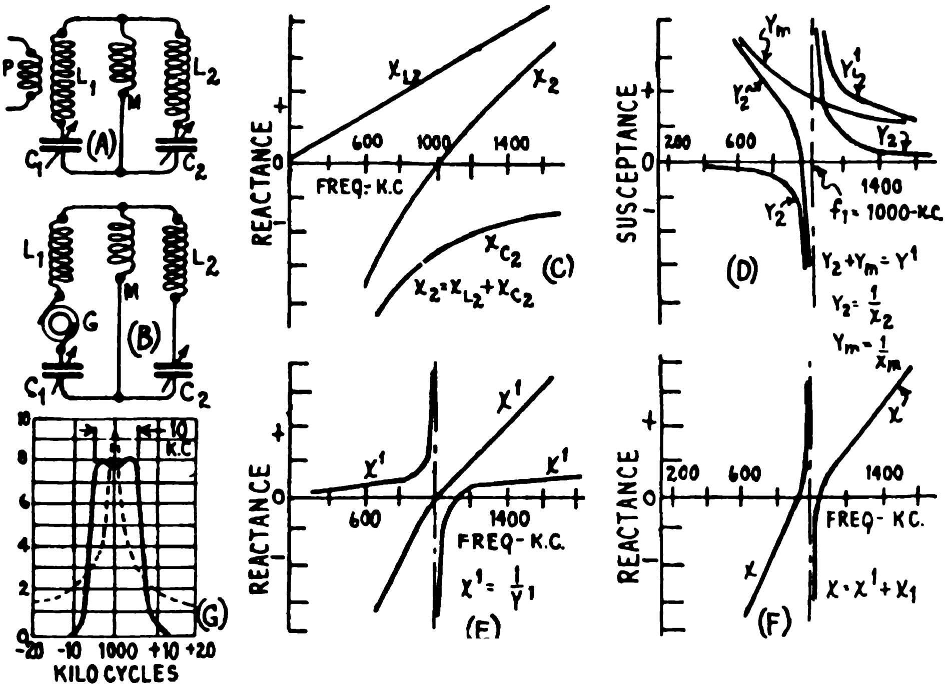


Fig. 256—Circuit arrangements and reactance variations in a band-pass filter

coils, etc. The input voltage E may be introduced by coupling L_1 by means of a primary coil as shown at (A), or by connecting L_1 directly in the plate circuit of the amplifier tube as shown at G of Fig. 257. The output may be taken directly from L_2 or C_2, or by inductive coupling from the circuit of L_2. Inducing a voltage in L_1 is comparable to placing the voltage in series with the coil, so that the equivalent circuit is as shown at (B), with the a-c generator G in series with L_1, supplying the input voltage.

A study of this diagram will reveal why the band-pass effect is obtained. Even though coils L_1 and L_2 are similar, and C_1 and C_2 may be set at exactly the same capacitance, the circuits in which they are placed are not tuned to exactly the same frequency simply because these circuits are not similar, due to the mutual coupling inductance or capacitance M, in the circuit.

The theory of all these filters is the same. One resonance frequency is determined by the circuit disregarding the coupling device. For example, in (A) the first maximum is determined by the two inductances L_1 and L_2 connected in series and the two capacities C_1 and C_2 connected in series. The circuit then consists of L_1, L_2, C_1 and C_2. The resonance point determined by these four impedances is exactly the same as that determined by one L and one C. The reason for this, is that the inductance of the two similar coils in series is twice the inductance of either coil, and the capacity of the two

equal condensers in series is equal to one-half the capacity of either. The second resonance frequency is determined by each half of the circuit in which the common or coupling impedance enters. For example, in (A) the second resonance frequency is determined by L_2, C_2, and M. Evidently this resonance frequency differs from the first one and will be more and more different as the coupling impedance M is made larger and larger.

We may make use of the reactance diagrams for the two parts of the circuit to find out just what happens in it for input voltages of various frequencies. It will be remembered from Article 175 and Fig. 116, that a reactance diagram shows how the reactance of an inductive or capacitive circuit varies as the frequency is changed. For any given similar settings of the tuning condensers C_1 and C_2, which in the case shown corresponds to a resonance frequency of 1,000 kc, the reactances of the inductance and capacity elements are calculated, plotted and combined to obtain the total reactances X_1 and X_2 of the circuits L_1 C_1 and L_2 C_2 respectively. Inductive reactance, equal to $2\pi fL$, is directly proportional to the frequency and when plotted for L_2 at (C) is a straight line (X_{L2}) through the origin. For capacitive reactance, the inverse relation $1/2\pi fc$ gives rise to the curve X_{C2} for condenser C_2. Since these two elements L_2 and C_2 are in series, their resultant reactance is obtained by adding algebraically the two curves, which determines the curve X_2. Curve X_2 indicates the well known series tuned circuit action; at the frequency to which the current is tuned, the reactance drops to zero.

In parallel with the branch "2" is the mutual reactance M, an inductance in this case. When elements are in parallel, the total susceptance is obtained by adding algebraically the individual susceptances, where any susceptance is given by the reciprocal of the corresponding reactance; that is, susceptance, Y, is equal to $\frac{1}{X}$. The reactance of M is a positive, straight-line function of frequency; when plotted as susceptance, it takes the inverse form of Ym in (D). The susceptance of the "2" branch is derived from the X_2 curve of (C). Where this reactance became zero at 1,000 kc, the susceptance goes to infinity. The sum of the two susceptances shows the curve Y^1, the total susceptance for the combination of M, C_2, and L_2. The construction shows that at 1000 kc the susceptance is infinity, and at a slightly lower frequency is zero; or, at respective frequencies, the reactance X_1 for the combination is zero, and infinity. The remaining circuit elements are C_1 and L_1, which are in series with the MC_2L_2 combination. The reactance curve for L_1 and C_1, in series, is X_1, similar to that for C_2L_2. Adding both series reactances yields the final overall curve, X, for the reactance of the band selector, which is drawn by itself for clearness at (F). The curves are plotted for a rather large mutual inductance, which is many times the actual inductance necessary in the common branch. If plotted for a smaller inductance, the points of zero and infinite reactance would merge indistinguishably close. As can be seen from (F), the reactance is zero at two values of frequency close together. At a frequency in between these, the reactance goes to infinity, and if reactance alone were considered, the current at this frequency should be zero. However, the resistance which is unavoidably present in the circuit limits the impedance so that it can never go to infinity, just as it can never go to zero. The consequence is a smoothing out of the current curves so that two resonant peaks occur at the points of zero reactance, and a more or less pronounced dip between them at the point of infinite reactance. The proximity of the peaks is determined by the value of the mutual impedance, or putting it another way, by the closeness of the coupling. As the value of the mutual inductance is increased, for any given frequency value, the coupling impedance goes up, and the peaks spread further apart as shown at (C), (D) and (E) of Fig. 257. On the other hand, increasing the capacity, when such is the common reactance, lowers the value of the coupling and the peaks come closer together. That changing the value of the common reactance changes the width of the selected band may be seen from the reactance curves. At (D) the point of zero susceptance, at f_1, is determined where the susceptance of M is equal

and opposite to the susceptance of the C_2L_2 branch. The higher the susceptance of M, the closer this point moves into the frequency f_1, and the narrower becomes the overall width of the selected band.

Because the band width varies with the value of the mutual reactance, for any given coupling inductance or capacity, the band width will vary for different broadcast carrier frequencies. Suppose the coupling has been adjusted for the desired band width at one particular carrier frequency; the band will be wider or narrower at higher or lower carrier frequencies, respectively, if the mutual reactance is a coil,—vice versa if a condenser—for the reason that the value of the reactance varies proportionally with the frequency. The voltage must be introduced in L_1 as shown.

At (G) of Fig. 256, is shown the sharp peaked tuning curve (dotted) produced by a single sharply tuned circuit of the ordinary type. The solid curve shows the characteristic almost flat-topped curve 10 kc wide produced by a well-designed band selector.

In the band selector system described above, the two tuned circuits may be coupled together by an inductance as at (A) of Fig. 256 or they may be coupled by a condenser M as at (A) of Fig. 257 The degree of coupling is changed by changing the capacity of condenser M. Making this smaller, increases the capacitive reactance, and this makes the response curve broader due to the increased coupling, i.e., the peaks are further apart as shown at (B), (C), (D) etc. The closer the coupling, the further apart are the peaks and the greater is the dip between them. The opposite effect is secured by making the capacity larger. The reactance of a coupling coil increases with increase of frequency while that of a coupling condenser decreases with increase of frequency. Therefore the tendency of a coupling coil is to broaden the tuning at high frequencies and that of coupling condenser is to broaden the tuning at low frequencies. Since the lower frequencies naturally tune more sharply than the higher frequencies, the effect of using a condenser for coupling is to compensate for this frequency effect, with resulting more uniform width of response curve for all frequencies. Consequently, most band selectors of this type use a condenser for coupling. When used with tuning coils of the size generally employed for broadcast band reception, the coupling coil M need have only about 1.5 microhenries inductance, four to six turns of wire on a one inch diameter form being about right.

The selectivity of the circuit depends on the sharpness of the tuning in the two tuned portions, because sharp tuning preserves the steepness of the sides of the response curves. Sharp tuning depends on the reduction of all forms of resistance in the tuned circuits. The broadness of the response depends on the degree of coupling used between the two circuits, the closer the coupling, the broader the response curve. The width of the response curve depends also on the frequency being received, the curve being broader at high frequencies and narrower at low frequencies.

One of the simplest band selector circuits is shown at (G) of Fig. 257. In the plate circuit of the first tube is the parallel tuned circuit including L_1 and C_1. The plate circuit is completed through the condenser C_3, and the direct plate current for the tube is supplied through the choke. In the grid circuit of the second tube is another tuned circuit with a similar coil and condenser, L_2 and C_2. If coils L_1 and L_2 are separated, each tunes to the same frequency if C_1 and C_2 are equal, and of course no band-pass effect is obtained. If the coils are placed near each other so that the magnetic field set up by the current in L_1 links with the coil L_2, the two are *magnetically coupled* (designated by M) and a band-pass effect is produced, the arrangement becoming resonant for two different frequencies

as explained for the previous circuits, the width of the band increasing as the coupling is increased.

The Vreeland band selector system is shown at (H) of Fig. 257. Here, two tuned circuits are coupled together through a mutual inductance consisting of a third coil L_3. The tuned circuit in the plate circuit of the first tube consists of C_1 L_1 and L_2. The tuned circuit for the grid circuit

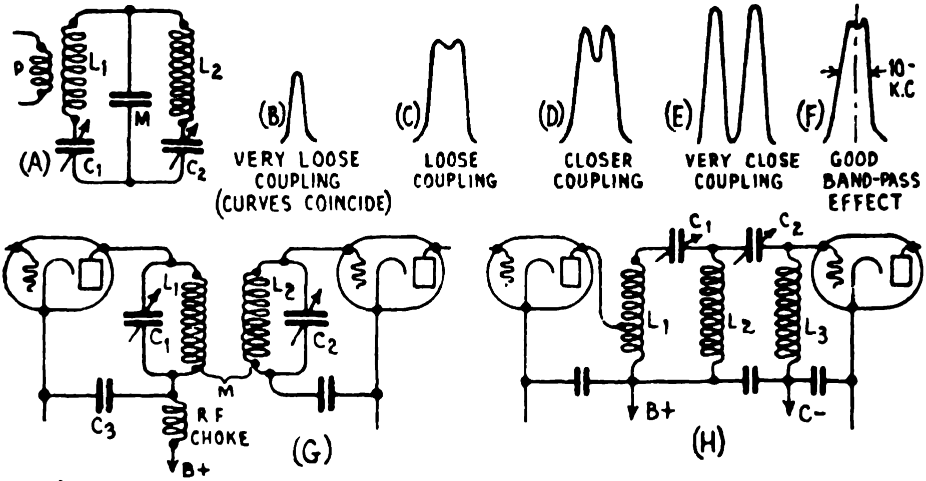


Fig. 257—Effect of coupling, on the resonance curves of band-pass filters Several band-pass filter circuit arrangements.

of the second tube, consists of tuning condenser C_2, coil L_2 and coil L_3. In general, the action of this system is similar to that just described.

The capacitively coupled filter of (A) of Fig. 257 has one advantage in that the band width increases toward the low-frequency end of the tuning range where a somewhat wider transmission band is desired for equal transmission of the side frequencies. This is undoubtedly the principal reason why this type of filter is used in most commercial receivers that use band passing at all. Another reason for its use is that it is somewhat simpler, especially as compared with the common coil-coupled filter.

361. Applications of band selector system: The various band selector arrangements just described may be used in several ways in radio receivers. The arrangements shown in Fig. 256 and at (A) of Fig. 257 are often employed ahead of the first radio-frequency amplifying tube of tuned r-f amplifiers. In this position they are commonly called *preselectors*. They are also employed in a special type of receiver which will now be described. The arrangement of (G) is used extensively in the intermediate amplifiers of superheterodyne receivers. We will study this system later.

In the radio-frequency amplifier systems thus far described in this chapter, selectivity and amplification are secured at the same time by

using successive amplifier tubes with a tuned circuit between each. Some receivers are designed to obtain this selectivity first, and then the amplification later. An example of this system is shown in Fig. 258. In this case, a band selector composed of several tuned circuits coupled together by means of coupling inductance M, is used to separate the signals of any wanted station from those of all other stations, and to transmit the wanted signals to an amplifier consisting of vacuum tubes coupled by untuned transformers, usually of 1 to 1 ratio.

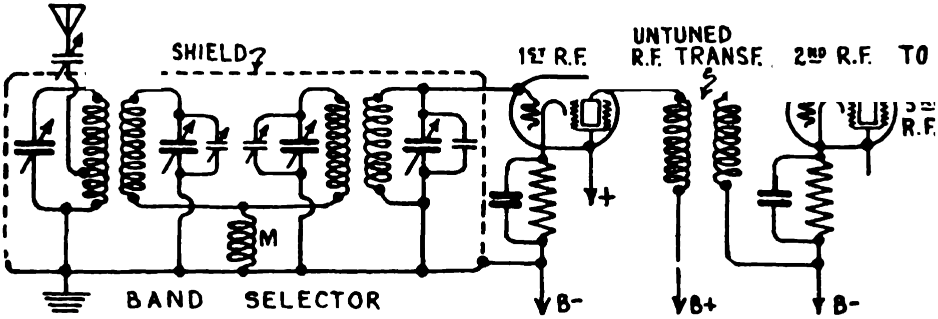


Fig. 258—A band-selector circuit employed in some receivers. All tuning is accomplished in the band selector. This is followed by untuned r-f amplifier stages.

Such an amplifier has no frequency discrimination, it amplifies all frequencies applied to it alike. It is not tuned at all—all tuning takes place in the band selector. An ordinary power detector and audio amplifier are used with the receiver. The outline diagram of this type of receiver was shown at (B) of Fig. 245. This type of circuit has been used successfully in many models of the Sparton and other commercial receivers. The practically "square-topped" tuning curve produced by the band selector eliminates sideband frequency suppression and aids in maintaining good audio tone quality.

362. Cross modulation and pre-selection: In the circuit diagram of the simple t-r-f receiver shown in Fig. 247, the signal voltages from the antenna circuit are fed to the grid circuit of the first r-f amplifier tube after being transferred to the tuned circuit L_2 C_2 by means of the antenna coupling transformer. In many receivers manufactured several years ago, a stage of fixed, untuned, radio-frequency amplification was employed between the antenna and the first r-f tube. This took the form of a resistor as shown at (A) or an r-f choke coil as shown at (B) of Fig. 259, connected directly in the antenna circuit and arranged so the varying voltage drop across it was applied directly to the grid circuit of the first r-f tube. The purpose of this arrangement was to eliminate the necessity of a tuned stage between the antenna and first r-f tube, since the tuning coil of such a stage would naturally be affected differently by the different inductances and capacitances of various antennas to which it

might be connected, thus causing its tuning to be way off and preventing proper synchronizing of each section of the gang tuning condenser employed for single tuning control. Such a stage did not harmfully affect the operation of the receiver when a '27 type tube was used in the first r-f stage. The high negative grid bias (13.5 volts) used with this type of tube allowed quite a large signal voltage to be applied to the tube without danger of running the grid positive or operating on the curved portion of the E_g - I_p characteristic of the tube (see Figs. 243 and 244). With the adoption of the '24 type screen grid tube as an r-f amplifier, troubles immediately arose. Modern broadcast receivers no longer employ the fixed input stage, but employ a tuned input stage loosely coupled to the antenna circuit in order to overcome the effects of antenna variation. The reduction in the strength of the signal transferred to the receiver, is offset by the increased amplification of the screen-grid type tubes employed. The '24 type of screen-grid tube operates with a negative grid bias of only 3.0 volts (see Fig. 214). This means that a signal voltage having a "peak amplitude" of over 3.0 volts (see Art. 343), will drive the grid positive during each positive half of the cycle, with the result that a grid current will flow in the grid circuit and this will reduce the selectivity of the receiver. To understand how this takes place, let us refer to Fig. 259:

The condition of the grid circuit when a sufficient grid bias is employed to prevent the grid from ever becoming positive due to the signal voltage, is shown at (C). The grid-cathode path acts as a small condenser and as such has no loss effect on the connected tuning circuit. But if this grid become plus, due to excessive signal voltage, electrons will flow from the cathode to the grid circuit, and this whole grid-cathode path becomes a resistance each time the grid becomes positive, as shown at (D). This resistance is located directly across the tuning circuit and broadens the tuning characteristic to that shown in curve "C" in Fig. 179. Unfortunately this broadening effect takes place on strong local stations right where the greatest amount of selectivity is desired. The overloading of the grid of the '24 type tube so that it becomes positive on strong signals is illustrated by the E_g - I_p curves at (E) of Fig. 259.

With a standard '27 type tube or other low mu tube, a much larger negative grid bias voltage is employed than is used with the '24 type. For instance, the '27 type tube calls for a 13.5 volt bias, when it is operated as an amplifier with 180 volts on the plate. Such a negative bias permits a 13.5 volt maximum "peak signal-voltage" swing in the radio-frequency circuits before the grid swings positive. For the '24 type tube at a plate voltage of 180 volts, a negative grid bias voltage of about 1.5 volts must be used. Therefore this tube can only handle signals having a maximum "peak voltage" of not over 1.5 volts, otherwise the grid goes positive and broadness of tuning and other things explained a little later on, will give trouble. There is a considerable difference between 13.5 volts and 1.5 volts when it comes to allowable peak signal voltage.

The plate-current, grid-voltage characteristics of both the '27 and '24 type tubes are plotted on the same scales at (E). Since the '27 type tube has a much longer straight portion of the characteristic than the '24, it is evident that it can handle a much stronger signal without distortion, as shown by the signal curves below. Of course, the screen-grid type of tube is used in spite of this because of the high amplification that may be obtained with it, and also because it has much less tendency to oscillate, due to its low plate-grid capacitance. Granting that the screen-grid type of tube is to be used on account of its high amplification factor and freedom from grid-plate capacitance, several precautions must be taken in the circuits in which it is employed if distortionless amplification is to be obtained.

First, due to the rather crowded lower part of the characteristic of the '24 type tube as shown at (F) strong second harmonic frequencies are produced if the strong signal of a local station acts directly on the grid of the first r-f tube. If no tuning cir-

cuit is used,—or even if only a single tuned circuit is used,—between the antenna and the first r-f tube, the grid of this tube will have impressed upon it, the signals of practically all stations at all times, no matter where the tuning condensers of the following stages are set. Thus, a strong powerful local broadcasting station may be pounding onto the grid of the first tube with sufficient signal strength to actually cause the tube to work over the curved lower portion of its characteristic and cause rectification in the plate circuit of that tube. We know that any rectification or detection will create audio currents which represent the program on the carrier wave. In fact, this is the

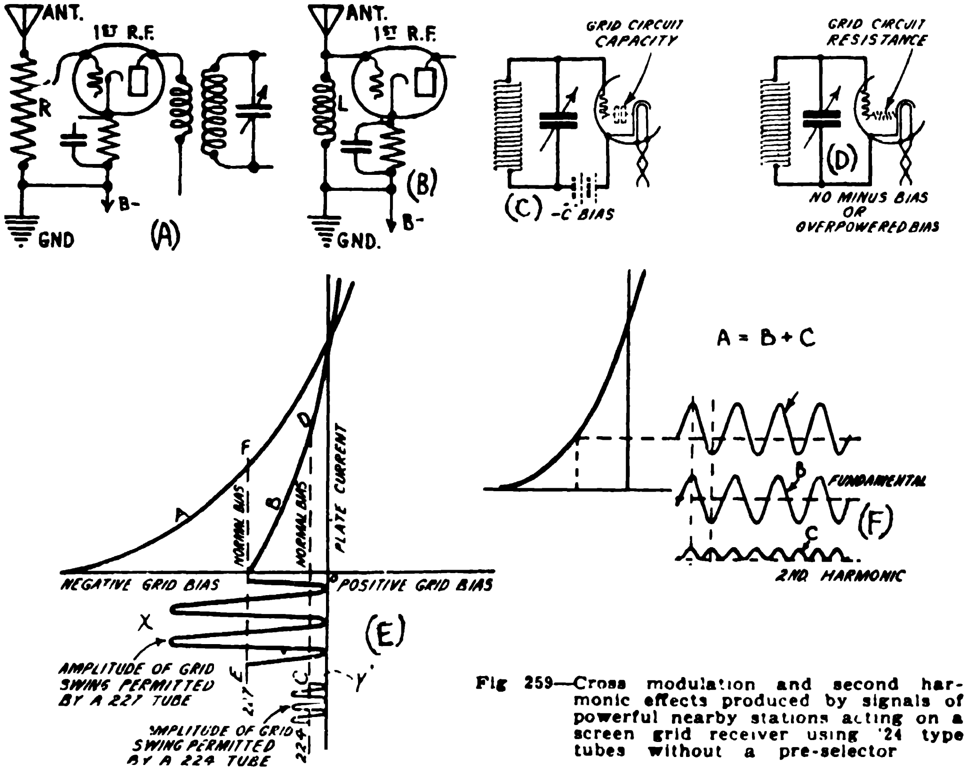


Fig 259—Cross modulation and second harmonic effects produced by signals of powerful nearby stations acting on a screen grid receiver using '24 type tubes without a pre-selector

entire action of the ordinary detector tube, and any tube, no matter how operated, will detect to some extent when the carrier signals are of sufficient strength to operate the grid at the lower bend. Thus, detection actually occurs in the first tube, and in appreciable amounts when the set is located near powerful local stations. The result of this is an effect commonly called *cross modulation* or *cross talk*. The local program may be tuned out all right on its own wavelength, but it will cause audio changes in the plate current. These will modulate the r-f variations caused by the signals of the station the receiver is tuned to. Thus the undesired local station program will be heard as part of the programs of all other stations received. This takes place regardless of how sharp the tuned circuits of the *following* stages are..

Another objectionable action which may take place is that of the production of second harmonic frequencies. We are already familiar with the fact that a curved E_g - I_p characteristic produces unequal amplification of the positive and negative halves of the incoming carrier signal voltage. This produces a lopsided amplified voltage in which the upper half is greater than the lower half as shown by curve (A) in (F). Such a voltage can be resolved into two voltages, both of which are symmetrical voltages. One has the proper frequency of the incoming signal and the other has twice

the frequency. The latter is known as the *harmonic.* This second frequency which is just twice the frequency of the proper one, is actually created in the tube and the amount of it, for a given strength of signal, depends on the steepness of the characteristic curve. Obviously, the '24 type screen-grid tube is a much more prolific source of second harmonic disturbance than the '27 type tube, since the latter has a "flatter" curve—see (E).

A study of (F) shows that curve A, which represents the actual plate current variations produced in the plate circuit of the tube, is the signal of the frequency of the station which it is desired to receive, and to which the receiver is tuned. This, of course is resolved into curves B and C. Curve B being of the same frequency, is the one which will be selected by the tuning circuits set for this frequency or wavelength. The new voltage of curve C which exists due to the fact that the original voltage waveform has been distorted, is exactly twice the frequency of the original signal voltage. Twice the frequency, means one-half the wavelength, and when the tuning condensers are set at one half the wavelength, possibly while tuning for another station, this new wave will be picked out and the program will be brought in again at this new setting. The result is that due to the second harmonics produced, the strong local

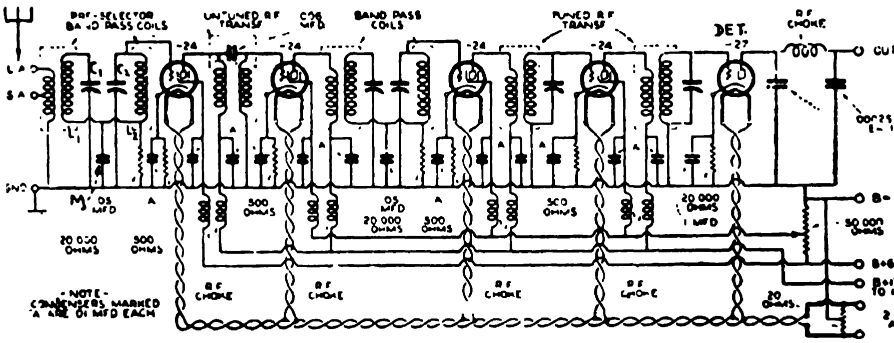


Fig 260—A 5-tube t-r-f amplifier using screen-grid tubes and a pre-selector ahead of the first r-f tube The pre-selector consists of a band-selector tuner.

station may be tuned in on two settings of the tuning condensers. Thus, even though it is say a high wavelength station, the fact that it is received again at a low wavelength setting may cause it to interfere with another low wavelength station operating near that frequency.

The remedy for these two effects, second harmonic generation and cross-modulation, is evidently to increase the selectivity ahead of the first r-f amplifier tube by coupling the antenna input through several tuned circuits to the grid circuit of the first tube. In this way, adequate selectivity will be obtained so that the signals of unwanted stations, even though they be powerful local stations, will not be strong enough after passing through the pre-selector tuner to either cause the grid of the first r-f tube to become positive, cause operation on the lower bend of the curve with resulting rectification and cross modulation, or cause second harmonics due to operation over the curved portion of the characteristic. The tuner arrangement is called a *pre-selector* because it "pre-selects" the wanted signals before they reach the first r-f amplifier tube.

Pre-selector circuits take several forms in practice but in most cases they consist of a band selector circuit with mutual inductive or capacitive coupling. A typical arrangement of this kind used in the r-f amplifier of an a-c operated receiver employing screen-grid tubes as amplifiers, is shown in Fig. 260. The audio amplifier and

power supply unit of the receiver are not shown. Tuning coils L_1 and L_2 and condensers C_1 and C_2 form the band selector with the common coupling condenser M. It should be remembered that all pre-selectors cause some reduction in the signal voltages of the stations they are tuned to, also due to the losses in the tuned circuits, loss of energy through imperfect coupling, etc. Of course the losses in well-designed circuits is less than in poorly designed ones; in the latter a reduction of signal strength of as much as 75 per cent may take place. The loss caused by well-designed circuits is not objectionable, since it can be made up for by more amplification in the r-f amplifier.

It is not to be inferred that all screen-grid receivers without preselectors suffer from cross-modulation. There are installations where small receiving antennas with resulting small signal pick-up are employed, with the result that the signals from local stations are not picked up strongly enough to cause cross-modulation. Also many receivers are operated in districts far enough away from all local stations so that extremely powerful local signals are not received. Also if variable-mu type screen-grid tubes are employed, the effects of cross-modulation and second harmonic production are very much reduced, due to the fact that this type of tube can handle an extremely large signal voltage without rectification or second harmonic distortion, due to its long E_g - I_p characteristic (see A of Fig. 230). Many receivers using variable-mu type r-f tubes are constructed without any pre-selection other than a single loosely coupled tuned stage between the antenna circuit and the grid of the first r-f tube. Cross modulation effects are very seldom troublesome in these, due to the characteristic of the variable-mu tube. This important feature has resulted in the extended uses of these tubes in modern radio receivers.

363. Variable tuning condensers: Variable condensers which are used extensively for tuning the fixed inductance coils in radio-frequency tuning circuits, to any carrier frequency within the receiving range of the set, consist of a group of stationary plates (stator) arranged so that a set of movable plates (rotor) can be moved in and out between them without touching. The dielectric (the space between them) is air.

Condensers of this type were described in detail in Articles 150 to 154. The reader is advised to review these at this time. When the plates are fully meshed, as shown at (A) of Fig. 98, the full areas of the plates are exposed and the *maximum* capacitance exists. When they are all out of mesh at (B), the minimum capacitance exists; and for any intermediate position between these as at (C), various intermediate values of capacitance exist. Tuning condensers are usually made with thin brass or aluminum plates supported by a rigid framework of brass or aluminum. The stator plates are held in position and insulated from the frame by insulating strips (see Fig. 99). The stator and rotor plates should not touch, for a short-circuit would then result. Rotor bearings should work smoothly and the entire condenser should be rigid.

The end of the tuning circuit which connects to the control grid of the r-f amplifier tubes, should always be connected to the *stator* plates of the tuning condenser. The other end is connected to the *rotor* plates, which are usually grounded to the metal shaft and frame of the condenser. Since this latter end of the tuning circuit goes to the B- or ground side of the circuit, connecting it this way automatically places the shaft and frame of the tuning condenser at or near ground potential. Then no capacity exists between the condenser shaft and the body of the operator

(which is also at ground potential), when it is to be rotated during the process of tuning. If the rotor shaft of the condenser were connected to the *grid end* of the tuning circuit, the capacity action between the body of the operator and the condenser shaft and rotor side of the tuned circuit, would form a capacity which is in effect really across the tuned circuit, since the other end is at ground potential through the B- line and ground. This would cause the resonance frequency of the tuned circuit to vary, de-

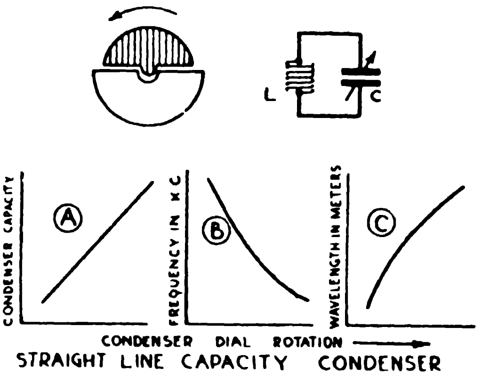


Fig 261—The capacitance of a condenser may be made to vary directly as the angle of rotation of the rotor plates, by using semi-circular rotor and stator plates

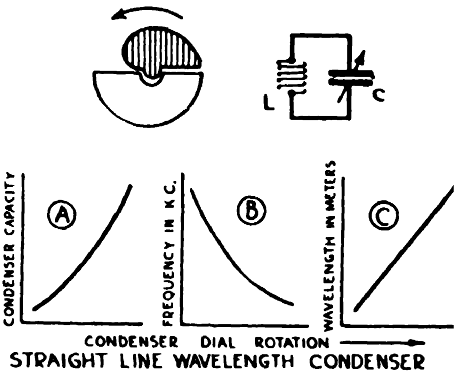


Fig 262—By tapering off the diameter of the advancing edge of the rotor, the angle of rotation may be made to vary directly as the wavelengths of the tuned circuit.

pending on how near the hand was to the condenser shaft, and this would cause a de-tuning action known as *hand-capacity* effect. This condition was very troublesome in old forms of receivers in which the condenser shaft was not grounded. On some receivers, after a station was tuned in, it would fade out completely (be de-tuned) as soon as the hand was removed from the tuning knob which was fastened to the rotor shaft.

364. Shapes of condenser plates: The capacity-variation of the usual form of variable condenser is caused by changing the amount of interleaving of the plates and hence the area between them. The rate at which the capacity changes as the plates are rotated depends on the shape of the plates. There are four well known shapes at the present time, devised to secure certain tuning characteristics when used with a coil in a tuned circuit. Each of these has certain definite applications either in radio receivers or testing equipment, etc.

365. Straight line capacity condenser: Fig. 261 shows a condenser with semi-circular rotor and stator plates.

In a condenser of this type it is obvious that the capacity is proportional to the angle of rotation of the rotor, or settings of the condenser dial. That is, for equal increases of rotation, equal increases of capacity are obtained. Therefore, it is called a *straight-line* capacity condenser. If a graph is plotted with dial settings against capacity, it is a straight line. Now if this condenser is connected to a fixed tuning coil L in the usual way, as the condenser is varied the circuit is tuned to various frequencies.

The variation of the resonant frequency with condenser dial settings is shown at (B). The curve becomes steeper at the lower end of the scale, showing that a given rotation of the dial near this end produces a much greater change in frequency or wavelength of the tuned circuit it is used in, than an equal rotation at the upper end of the scale. Therefore, since the carrier frequencies of broadcasting stations in the same vicinity differ by at least 10 kilocycles, it will only require a small rotation of the condenser shaft and rotor plates to change the resonance frequency of the tuned circuit 10 kc to tune from one station to the next, at the lower end of the scale (high frequencies). Hence, if a tuning condenser having semi-circular plates is employed in a radio re-

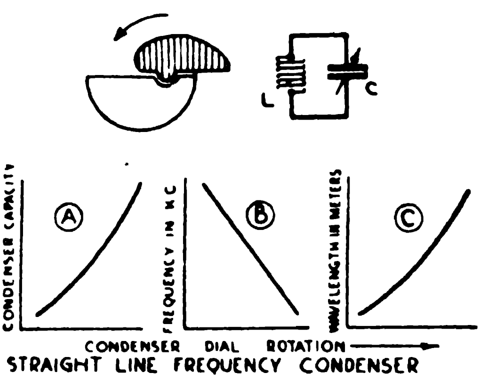


Fig 263—By properly shaping the plates the resonance frequency of the tuned circuit may be made to vary directly as the angle of rotation of the rotor plates

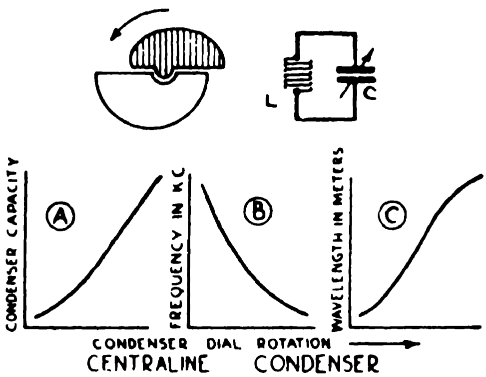


Fig 264—Proper shaping of the plates produces a "Centraline" or "Mid line" tuning curve which is most suitable for the tuning circuits of radio receivers

ceiver, a great many stations will be received over a small crowded portion of the dial at the low wavelength end, making it necessary to set the tuning condenser extremely accurately if only a single station is to be received at a time. Therefore this simple plate shape is used very little in modern radio receivers. It is useful however, in laboratory and testing work where equal increases of capacitance are desired for equal angles of rotation of the rotor plates.

366. Straight line wavelength condenser: Many years ago, a type of condenser having a plate shape such, that equal angles of rotation of the rotor plates produced equal changes in the *wavelength* of the tuned circuit, (see Fig. 262), was used extensively in wavemeters, designed to measure the wavelength of transmitting stations, etc. This is called a *straight-line wavelength* condenser. This made a convenient form of condenser for the purpose, since the dial could be calibrated directly in wavelength and equal divisions on it would represent equal changes in wavelength.

An attempt to reduce the crowding of stations at the low wavelength region of the tuning scale in broadcasting receivers, was made by using tuning condensers having plate shapes designed to produce straight-line wavelength tuning variations. Since the wavelength-rotation curve is a straight line as at (C), a given change in dial setting anywhere produces the same change in wavelength. But the carrier waves of broadcasting stations are not separated by equal wavelengths, so that actually with this type of condenser the low wavelength stations are still crowded at the

lower end of the dial, although there is a decided improvement over the S. L. C. type. The stations at the upper wavelengths are also crowded. However, the separation of the stations around the middle of the dial is practically perfect. This type of condenser is useful in wavemeters or oscillators where it is desired to have the dial reading proportional to the wavelength.

367. Straight-line frequency condenser: The *straight-line frequency* variable tuning condenser (S. L. F.), is designed with a plate shape which makes the rotation of the dial proportional to the resonance *frequency* of a tuned circuit in which it is used. With this type of condenser (Fig. 263) stations separated by 10 kilocycles in frequency come in at equally separated points on the dial. The trouble is that the high power broadcasting stations are distributed, in general, over the upper end of the scale. Hence it is of great importance that the latter be separated properly. The S. L. F. condenser does not do this, but rather crowds both the higher wavelength stations and those around the middle band, under the present station locations and frequency separations. Therefore it does not quite solve the problem of spreading the received stations out uniformly over the tuning dial of the receiver. This type of condenser is useful in oscillators and wavemeters or frequency-meters, where it is desired to have equal divisions on the dial indicate equal changes in the frequency.

368. Centraline tuning condenser: Condensers having rotor and stator plate shapes such as to produce a desirable compromise tuning curve when used in the tuning circuits of radio receivers, have been designed and are in common use. These condensers commonly known by such names as "Centraline" "Midline", etc., are designed to eliminate the disadvantages possessed by the other forms described by employing special plate shapes which give a composite tuning curve, that is, give approximately S. L. F. tuning at the low end of the dial, S. L. W. tuning at the center region, and S. L. C. tuning at the upper wavelengths. A study of the curves in Fig. 264 will show this.

These desirable tuning characteristics can be secured by irregular shaping of either the rotor plates, stator plates, or both. The physical dimensions of the condenser should be kept small, so that not much space will be required when installed in a receiver. A rotor plate shape designed to produce this effect is shown in Fig. 264 and at the right of Fig. 265.

It is evident that the effect of the S. L. W., S. L. F., and Centraline condenser plate shapes is strictly a slow-motion action on the capacity variation, having a variable reduction and gradually changing as the condenser is advanced. The same result can be accomplished by a slow-motion vernier dial constructed to automatically vary its reduction ratio to give the effect of any of these shaped plates when used with an S. L. C. condenser, but shaping the plates to produce the desired result is a much cheaper and simpler method for it costs no more to punch out condenser plates with special shapes than it does to punch out semi-circular plates, after the proper punching dies have been made up.

The illustration of Fig. 265 shows one of each of the types of condensers described, showing the shapes of the plates used in each. As explained in Article 150, variable condensers used in receiving sets are made in various capacitance values, some of which have become fairly well standard in the United States. Also they are made in single sections or in gang form, with 2 or more sections arranged to be varied in capacity by the movement of a common rotor shaft as shown in Fig. 100 and at the left of Fig. 268.

369. Reduction of tuning controls: A study of the circuit diagrams of multi-stage t. r. f. amplifiers already studied shows that the

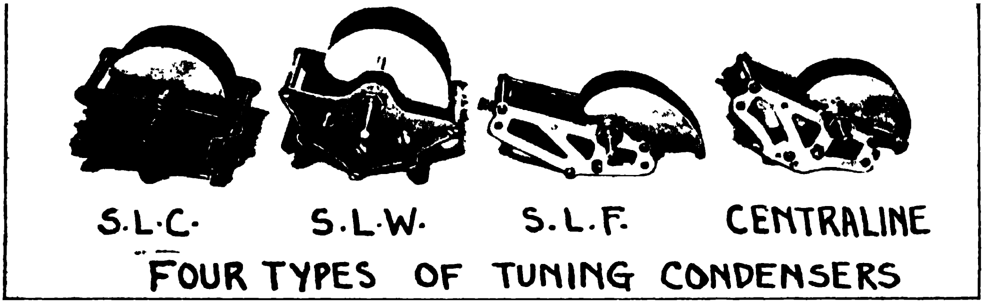


Fig. 265—Four tuning condensers designed to produce various definite capacity-variation and tuning characteristics by using the various plate shapes shown

tuning of the receiver from one station to another is accomplished by rotating the rotor plates of the several tuning condensers. Referring, for instance to the simple 3-stage t-r-f amplifiers of Fig. 247, we see that in order to tune from one station to another, the shafts and rotor plates of condensers C_2, C_3, and C_4 must be turned in order to obtain the proper capacitance value *in each tuned circuit*, to tune the receiver to the frequency of the new station. If three condensers with separate shafts and controls were used for C_2, C_3, and C_4, this would mean that three condenser knobs or dials would have to be manipulated simultaneously.

It is rather awkward to manipulate 3 things carefully, and in step with each other, with two hands. Now the tuned circuit L_3 - C_3 works out of the plate circuit of the first r-f tube and into the grid circuit of the second one, (a similar tube). The same thing is true of tuned circuit L_4 - C_4. Therefore, if the coils L_3 and L_4, the condensers C_3 and C_4, and all stray capacitances and inductances associated with the tuned circuits are exactly similar, the two condenser settings will be exactly similar when any station is tuned in. Therefore some means can be employed to mechanically couple or *gang* the rotor shafts of these two condensers together, so they may be turned exactly in step with each other by a *single* knob or tuning *control*. We will consider the various mechanical schemes possible for ganging, presently.

It is important at this point to see just what stray inductances and capacitances may be present in either of the two tuned circuits considered. If we analyze the simple tuned grid circuit shown at (A) of Fig. 266, we find that actually it is not as simple as it seems. There are several additional capacities acting in the circuit, as shown at (B). Here

we have the pure tuning inductance L, and the total circuit capacitance C consisting of the sum of the following capacitances.

d=effective capacitance from coupled input circuit.
e=distributed capacitance of the coil winding.
f=capacitance of the tuning condenser proper.
g=input grid-cathode capacitance of the vacuum tube and the capacitance between all wiring to the grid and cathode.
h=capacitance between the coil, wiring and any metal near the coil, such as shielding, etc.

Now the capacitance d, will vary with the degree of coupling and the type of input circuit, i.e., whether it is an antenna or the plate circuit of a preceeding tube; e and h will vary with type of coil winding, shape of coil, spacing, size of coil, size of shield, etc.; g will vary considerably with the type of plate loading. It is evident that in order to obtain practical single-control of the tuned r-f stages, in the receiver, *not only must the tuning coils and condensers be accurately matched, but these various stray circuit capacitances must also be kept similar in value in each stage.*

When we come to the antenna input stage several other factors enter into the problem of single-dial tuning control.

370. Effect of antenna on single-dial tuning control: It has already been shown in Fig. 179 that an antenna acts together with the earth to form a condenser. For high frequency currents there is some inductance in the straight aerial, lead-in and ground wires. It follows that an antenna has both inductance and capacitance, distributed along the length of the wire. Therefore the antenna really forms a series tuned circuit as shown at (B) of Fig. 179.

The *fundamental frequency* of an antenna is that for which the maximum possible current will flow, when no additional coils or condensers, etc are connected to it. It can be shown mathematically that when the length (in meters) of an antenna of the single wire vertical or L type is approximately one-fourth of the wave length (in meters), the fundamental frequency is that for which the sum of the inductive and capacitance reactances are zero. The length of an L type antenna includes the length of the horizontal portion plus the total length of the lead-in and ground wires.

Example: It is desired to erect an inverted L antenna which is to have a fundamental wavelength of 400 meters. What must be its total length?

Solution: 1 meter equals approximately 3.3 feet. Therefore 400 meters equal approximately $3.3 \times 400 = 1{,}320$ feet. Therefore the total distance from the ground up through the ground lead, the antenna lead and the horizontal top portion, should be about $1320 \div 4 = 330$ feet. In practice the length may vary considerably from this value.

The wavelength to which any resonant circuit is tuned may be increased by increasing either its inductance or capacitance. The wavelength of an antenna is therefore increased by connecting an inductance or *loading coil* in series with it, since then the actual inductance in the circuit is the sum of the inductances of the antenna and the coil. If a condenser is connected in series with the antenna, the wavelength is decreased, since now the combined capacitance of the antenna itself and the capacity in series with it is less than that of either alone.

When we connect the receiving antenna to the input tuning coil therefore, we have the condition shown at (C) of Fig. 266. The antenna capacitance C_A and the antenna inductance L_A are acting in series with the primary winding P of the antenna coupling coil. It is evident that the

tuning circuit consisting of L_1 C_1 must work under somewhat different conditions than L_2 C_2 due to the effect of the antenna capacitance and inductance on the circuit. The capacitance of the antenna circuit acts like a similar condenser C, connected across a portion of the secondary. Therefore, to tune the antenna system through the broadcast band, and yet use a gang condenser for all the tuned circuits including the antenna, a different type of tuning condenser would be required for each individual an-

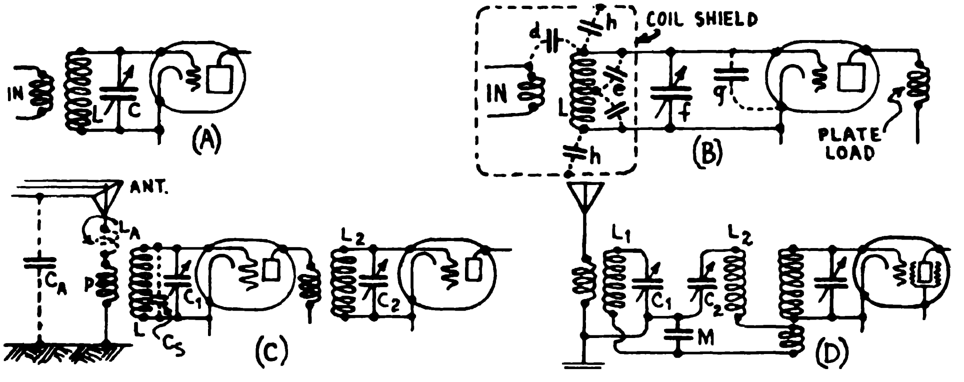


Fig 266— Study of the effect of antenna circuit capacitance, and stray capacitances, on the tuning circuits of a t-r-f amplifier These are important in single-control receivers

tenna system which the set might be used with. This would be commercially impractical.

371. Antenna coupling systems: One remedy for this condition would be to leave the antenna stage untuned, and couple it to the first r-f tube by any of the arrangements shown in Fig. 267.

At (A) the first r-f tube is coupled to the antenna by a resistance of about 2,000 ohms. The varying voltage drop appearing across the end of the resistor due to the flow of the varying antenna circuit current, is applied to the input circuit of the first r-f tube commonly called the "coupling tube". This tube does not add any amplification to the circuit, but acts merely as a coupling device With this arrangement the antenna constants have little or no effect upon the tuning of the following circuit. However, an untuned antenna stage usually produces harmonics and "cross modulation" due to rectification being set up in the first r-f tube by strong local signals as explained in Article 362. The audio currents produced in its plate circuit modulate the incoming r-f signals of all other stations, and thus the local station signal is heard as a modulation on all other stations received.

If a variable resistor R is employed as at (B) it can also be used as a volume control by varying the fraction of its total resistance and voltage drop which is included in the grid input circuit of the tube. Another method where an r-f choke coil is used to produce a potential difference between the grid and cathode is shown at (C). In some cases it has been possible to secure a small voltage step-up in the coupling tube T by utilizing a choke coil connected between the antenna and ground which, in conjunction with the average antenna (capacity about 150 to 300 mmfd, inductance from 50 to 100 microhenries, and resistance of 25 to 100 ohms), tunes to approximately 200 or 300 meters, and provides a voltage step-up in the neighborhood of four at resonance, and diminishing to about one for the remote frequencies. Unfortunately all that can be said for all of these types of antenna coupling is that they solve the single-

control problem. They contribute nothing to the selectivity of the receiver, since they accept signals of all frequencies, excepting the case of the choke coil coupling. The latter may contribute some voltage gain if the inductance of the choke tunes the antenna capacitance to some frequency in the broadcast band. The amplification thus secured is confined, however, to a narrow band of frequencies around this fixed resonant frequency. At all other frequencies the gain is practically nil. Also the frequency at which some gain is obtained due to resonance will vary with different antennas.

All of these methods are very liable to cause "cross modulation" as explained above and they are seldom used in modern receivers, although many receiver models manufactured several years ago did employ them on account of their simplicity and effectiveness in eliminating the effect of the antenna circuit on the tuning of single-control receivers. In recent models of commercial receivers, the problem has been met in two ways. One is to use a variable inductance or "variometer" having a high ratio of maximum to minimum inductance, in the place of the fixed choke coil at (C), this variometer tuning the antenna circuit to resonance for the frequency of each station being received. While this type of tuned antenna input circuit applies about 3 times as much signal voltage to the grid of the first tube as the untuned antenna system does, it has the objection of adding an extra tuning control to the receiver. Many receivers now use an aperiodic (untuned) antenna circuit with an r-f transformer as shown at (C) and (D) of Fig. 266.

There are two types of antenna transformers in use, one having a high-impedance primary and the other a low-impedance primary. Both of these transformers, when properly designed, give good selectivity characteristics, gain, and practically freedom from cross-talk. They also satisfactorily meet the problem of antenna-stage tracking for single-control sets. In the high-impedance primary type, the primary of the transformer is usually slot-wound and has an inductance of the order of 400-700 microhenries. It tunes the antenna capacity to a low frequency just outside the broadcast band. Long-wave gain due to resonance is therefore high in comparison to the short-wave gain. Very loose coupling of the order of 10 per cent is employed. Antenna reaction reduces the effective secondary inductance, but owing to the very loose coupling employed, this is of small magnitude, and easily compensated. The gain of

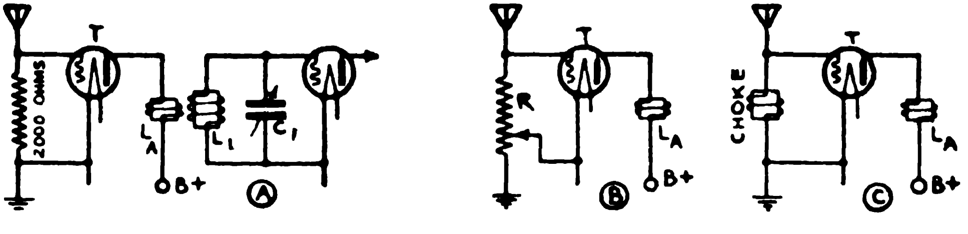


Fig 267—Several methods of "direct coupling" the antenna circuit to the grid circuit of the first r-f amplifier tube

this system decreases with increasing frequency, but this tends to straighten out the over-all gain curve of sets employing conventional type r-f interstage transformers.

The antenna transformer with low-impedance primary, was the most widely used system in battery sets, some years ago, especially two-and three-control sets. The primary consisted, generally, of about 6 to 20 turns (depending upon the type of transformer employed). The coupling coefficient was as high as 40 per cent and it was necessary to resort to very tight coupling in the antenna stage in order to get better transfer of signal voltage at the upper wavelengths. However, this tight coupling was unsatisfactory at the lower wavelengths. First the capacity reflected from the antenna

circuit into the secondary was so great that it was not always possible to tune the first stage down to 1500 kilocycles. In the second place, the loading due to the antenna, and the dielectric loss between the primary and secondary were both increased, resulting in very poor selectivity characteristics for the first stage. It was, therefore, necessary either to reduce the coupling by reducing the primary turns by means of a tap on the primary, or to shorten the antenna electrically by the use of an antenna series condenser. The use of a single antenna connection was therefore not satisfactory over the entire frequency band.

Of course, loose coupling between the primary and secondary of the antenna coupling transformer means that only a small portion of the signal energy in the antenna circuit is transferred to coil L_1 and the grid circuit of the first tube. It does however, effectively reduce the effect of the antenna on the tuning of the first tuning condenser C_1 to such an extent, that this condenser may be ganged with the other tuning condensers. Designers of broadcast band receivers at least, have preferred to make up for this loss by employing more radio-frequency amplification in the set—this being a rather simple matter when high-gain screen-grid variable-mu vacuum tubes are employed. When a pre-selector or band-selector system is used, as shown at (D) of Fig. 266, the same loose coupling between the antenna circuit and secondary L_1 of the tuning coil may be employed.

In some cases a small variable condenser is connected in series with the antenna as shown in Fig. 258. This not only reduces the effective capacitance of the antenna (since it is in series with the antenna capacitance), but also permits some adjustment of the effective total antenna capacitance when different lengths of antenna are used. This condenser usually takes the form of a "midget" condenser of from .0001 to .0005 mf.

372. Condenser ganging: After the circuit arrangements and constants of the r-f amplifier have been satisfactorily worked out in accordance with these conditions to permit simultaneous tuning of all stages by a single control of the tuning condensers, the problem resolves itself into devising some mechanical arrangement for turning the rotor shafts of all of the tuning condensers simultaneously by means of a *single tuning control.*

Several mechanical arrangements have been devised for this purpose, but only two of them are still employed to any extent. Arrangements in which the shafts of the separate tuning condensers were connected through racks and pinions, systems of parallel arms and levers or cranks, or by flexible metal belts and pulleys have been used. Of these methods, the latter is the only one which has survived. In this, each condenser shaft is provided with a pulley which is driven by a flexible phosphor bronze belt with tension adjustment, from the main driving pulley. This in turn is controlled (usually with a step-down ratio), by a single tuning knob.

The more common method because of its cheapness, compactness and simplicity, is to build all of the condenser sections into a single frame and with a common rotor shaft, so that motion of this single rotor shaft turns all of the rotor plates simultaneously. This is called a *gang condenser.* Of course, a condenser of this type may be built with as many sections or gangs as desired. A 4-gang condenser of this type was shown in Fig. 100. A 5-gang tuning condenser is shown at the left of Fig. 268. A grounded

flat metal plate (electrostatic shield) between each section of the gang reduces the capacitance which exists between adjacent stator sections when the rotor plates are turned out. As will be seen from the chart of radio symbols in Appendix A, a gang condenser is indicated by the common stator-plate line. In some cases, the condenser sections are each shown separately, but the rotor plates are connected by a dotted line. At (B) of Fig. 268, the connections of the secondaries of five r-f transformers to the individual sections of the 5 gang condenser are shown. The primaries are omitted for simplicity. The connection of each tuned stage to the grid of the amplifier tube is also shown. Note that the rotor and frame of the condenser form the common grid-return side for all the tuned circuits. A 5 tube t.r.f. amplifier in which several tuned circuits are tuned by a gang condenser is shown in Fig. 260. This permits the simultaneous tuning of all the circuits at once by merely turning a single knob or dial fastened to the condenser shaft.

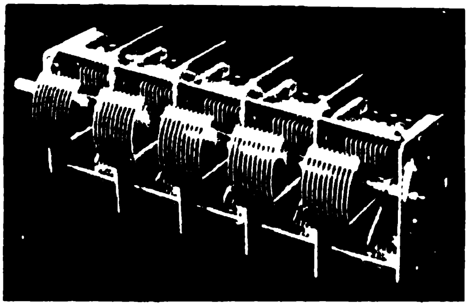
373. Equalizing the circuits: In order to obtain maximum sensitivity in receivers using gang control of tuning condensers, it is absolutely essential that every tuned stage in the amplifier be tuned to exactly the same frequency for any one setting of the dial. This means that when once the various stages are adjusted to tune in step with each other, they should continue to "track" together over the entire range of the receiver. If one or more of the stages tunes to a higher or lower frequency than the rest, that stage is not set at exact resonance to an incoming signal when the others are, and therefore it produces less amplification than it otherwise would. In order to make the various tuned stages track up perfectly, it is necessary that the total of the capacitances and inductances in each tuned circuit be exactly equal. This means not only the capacitance of the tuning condenser and the inductance of the tuning coil but also all of the stray inductances and capacitances which may affect the tuned circuit, as shown at (B) of Fig. 266.

The first essential of success with gang-controlled receivers is that all the condenser sections in the gang have the same *rate of capacity change* at all settings, that is, over the entire tuning range of the circuit. All the condensers do not have to have the same maximum capacity, for any differences in this respect can be compensated in the inductances. But it is preferable that all the sections be equal, for if they are, there is a better chance that all the sections will have the same rate of capacity change at every setting.

If condensers having semi-circular plates (S.L.C.) are used for tuning, the adjustment for bringing various stages into step can be made by providing suitable adjustments enabling the entire set of rotor plates of any one condenser to be advanced or retarded in order to increase or decrease the capacitance at all settings or by adding small compensating condensers in parallel with the tuning condensers. If this is done with condensers having other plate shapes (as S. L. W., S. L. F., and Centraline), the capacities become unbalanced as the tuning dial is advanced. This is due to the fact that in these forms of condensers the *capacity variation per dial division increases* as the condenser is turned toward maximum capacity, and the unit which was advanced gains capacity more rapidly than the others. This can be partly avoided by keeping all the rotor plates exactly in step and making up for any inequalities by means of small compensating condensers which can be set and left fixed, thus adding a constant capacity to each circuit, as explained in Article 152. This method is not entirely suitable however, for it is very possible that the tuned circuits may be adjusted

to be exactly in step for one frequency and they will be out of step at other frequencies if the various sections of the gang condenser do not vary in capacity *at similar rates* as the condenser setting is varied. This action was very noticeable on the early forms of single control receivers which employed simple gang condensers, with a small compensating condenser built into each section of the condenser. The tuned stages could be adjusted to track perfectly at any one small range of frequencies but they would be out of step for frequencies above and below this. As a compromise, receivers of this kind were tracked up accurately at but one setting at the center of the tuning range, but of course the sensitivity for all settings above and below this was much lower.

One way of eliminating this very objectionable feature, is to have one of the end rotor plates of *each section* split radially or fan-wise to form about 5 or 6 segments, as shown in the condenser of Fig. 268. The tuning of each of the various circuits can then be aligned at 5 or 6 separate points equally distributed over the entire tuning range by slightly bending the slotted segment which is just entering the stator plate area. If it is bent toward the stator plate the capacity is raised; if it is bent out, the capacity is lowered. This may be done while a station of that frequency is being re-



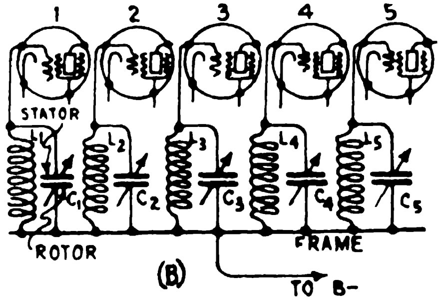


Fig 268—Left A 5-gang tuning condenser Notice the slotted rotor plate at the end of each section
Right Connections of the secondary windings of 5 r-f tuning coils to the 5 sections of a 6-gang condenser in a single dial receiver

ceived, or while a signal from a local test oscillator is being impressed on the receiver. The condensers are considered to be adjusted properly when maximum output is obtained. Since the ear is rather insensitive to changes in intensity of sound, more accurate adjustments may be made by employing an output meter such as that shown in Fig. 153 for indicating the output of the set during the adjusting process rather than relying on the loudness of the sound issuing from the loud speaker as judged by the ear.

As it is rather difficult to bend the segments delicately and accurately by hand, one form of gang condenser employs a set-screw arrangement shown in Fig. 269. The set screws go through a solid plate fastened to the rotor shaft They are arranged so that the end of one screw presses against each section of the slit plate. By turning the screw, the segment it rests against can be pushed in or out by a very small amount if necessary. Adjustment is usually made with the receiver tuned to 1120, 840, 700, 600 and 550 kilocycles. The five positions of the rotor for these adjustments are shown in the illustration

When a gang condenser is used, the coils must be carefully wound and matched, in order to minimize any inequalities between them. In spite of careful manufacture, they are bound to differ slightly so the coils must be tested and the inductance value adjusted before they leave the factory.

One simple way of doing this is to wind the coils with the inductance slightly larger than the value required Then they are tested and the inductance may be brought down to the exact value required by sliding a few of the end turns outward toward the end of the coil so they are more widely spaced, thus placing them in the weaker part of the field and thereby slightly decreasing the inductance. This is shown at (G) of Fig. 79, and is a very simple and effective means of producing slight reduction in the inductance. Of course if the inductance is much too high, some turns

of wire must be removed altogether, if it is much too low, turns must be added. A coil having too low an inductance requires more tuning capacity for any given frequency than those of proper value do. One whose inductance is too high requires less tuning capacity than those of proper value do.

If metal shielding is used around the coils, it will also affect the inductance, as does any metal object or conductor which may be in the field of the coil. The fact that the surroundings of a coil affects the inductance indicates the necessity of putting all the coils in similar settings. For example, shields around or near a coil will change its effective inductance, and this change depends on the frequency. The change is usually a decrease in the inductance, because of the bucking effect of the induced *eddy* currents in the shielding. The remedy for any inequality from this effect, obviously, is to mount every coil in the same manner with respect to shielding. And since different metals will react differently it is important that every shield should be of the same type and thickness of metal. (Note: Shielding is discussed in Arts. 412 to 414.)

Still another reaction effect is that of the primary on the secondary. The mutual inductance between the primary and the secondary will change the effective induc-

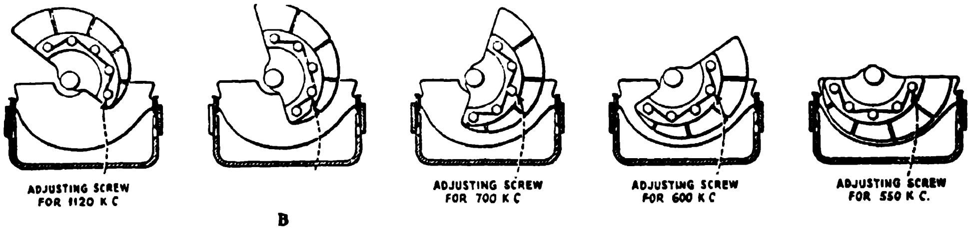


Fig 269—Slotted condenser end-plate construction with set-screw adjustment for tracking up the tuning The rotor is shown in 5 different positions at which the segments are adjusted to align the tuned circuits

tance of the secondary and hence the required capacity to tune the secondary to a given frequency. This demands not only that the primaries be equal but that they be placed in the same manner with respect to the secondaries, unless loose coupling is employed between the primary and secondary coil as in the case of the antenna coupling transformer. Not only that, but it demands, as a rule, that the primaries be preceded by the same type of tube similarly operated. This effect also depends on the frequency and therefore it is somewhat troublesome. The inductance value of a coil is changed by the presence of other conductors in the field. The distributed capacity is constant as long as the coil is fixed in position, and therefore the distributed capacity adds to the zero setting capacity of the condenser and can be compensated for by the trimming condensers.

The actual procedure to be followed in adjusting or "aligning" the tuned stages in receivers employing gang condensers will be considered in detail in Articles 632 to 639 in Chapter 35. Illustrations and circuit diagrams of receivers employing gang condensers for single-control will be found in the chapters on Superheterodyne Receivers, The Battery Operated Receiver and Electric Receivers.

374. Purpose of the volume control: We have proceeded with our progressive study of tuned radio-frequency amplification to the point where we are ready to consider the various forms of volume or gain controls which may be utilized to control the loudness of the sound issuing from the loud speaker.

Assuming that our receiver employs a detector preceded by several stages of radio-frequency amplification, and followed by one or more stages of audio-frequency amplification (which will be studied presently), it would seem that some form of volume control device could be introduced

either in the r-f amplifier or in the audio amplifier, so as to reduce the signal voltages applied to the amplifier tubes. The volume control in a complete radio receiver is seldom placed entirely in the audio amplifier for the simple reason that even if it were turned down to a low setting when a strong local station were being received, the last r-f amplifier tube, or the detector tube, would be overloaded, with resulting distortion, since the full amplified r-f signal-voltage is being applied to these. The volume control

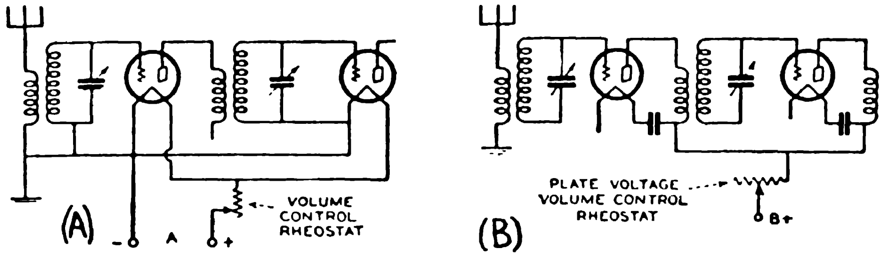


Fig 270—(A) Simple battery receiver volume control by varying the filament voltage. (B) Volume control by varying the plate voltage.

is therefore placed before the detector tube, in order to prevent overloading of these tubes under such conditions.

The volume or gain control unit in a receiver is utilized in most cases to reduce the volume of strong signals. For weak signals, it is usually set at maximum. Volume control methods and arrangements have passed through a series of changes in the past few years due to changing designs of receivers and the change from battery operation of receivers to a-c electric operation.

Receiving sets are being designed with sensitivities of the order of 1 microvolt per meter. That is, when a signal voltage of 4 millionths of a volt is produced in the receiving antenna, a "normal" (mildly comfortable) loud speaker signal is produced when the volume control is set at its maximum volume position. Such an antenna signal might conceivably be produced in an antenna located several hundred miles from a powerful broadcast station. This same antenna and receiving set located in a more favorable position, say one-half mile from the broadcast station, might conceivably have induced in it as large a signal as 1 volt or more, at least 250,000 times as great a signal as in the preceding case. Obviously such a signal would cause severe overloading of all the tubes unless it were controlled. In order to obtain a "normal" signal from the loud speaker with this 1 volt input signal, a signal reduction or *attenuation* of 250,000 would have to be caused by the volume control in one way or another. Also, when the volume control is set at its minimum-volume position, no signal should be heard. The volume control must then introduce additional attenuation to completely extinguish the "normal" signal produced after attenuating a 1 volt antenna signal 250,000 times. If we assume this additional required attenuation to be four, the total attenuation required of the volume control amounts to 1,000,000. In other words, the volume control must be able to effectively control various signals which may differ as much as 1,000,000 to 1 in intensity.

375. Volume control arrangements: Volume control should not be obtained by detuning the tuning condensers from the exact point of resonance when a station is being received, for that is apt to bring in interference from other stations which are thereby being tuned in. It should be obtained by a form of control which does not affect the tuning. Various volume control arrangements using non-inductive resistors will now be described.

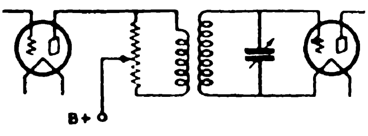
Possibly the most simple form of volume control used extensively in battery operated receivers, consisted of connecting a simple wire-wound rheostat of the order of

4 to 20 ohms, depending on the type and number of tubes controlled, in series with the filament circuit of the radio-frequency or detector tubes, as shown at (A) of Fig. 270. By controlling the filament current, the emission and amplification of these tubes was controlled. While this method of volume control is satisfactory for use with battery operated receivers, it is unsuited for those using separate-heater type tubes, because the cathode element has such high thermal inertia that there is an appreciable time-lag between the filament current changes, and the temperature and emission. When the signal became too loud, the vol.-control would be adjusted. Owing to the thermal inertia nothing would happen for a while. When the cathode finally reached its constant temperature corresponding to the changed current, the signal would suddenly drop and it would then probably be too low. The volume control would then be turned up and the same thing would happen, except that now the signal might now be too great or still not loud enough. After a few adjustments, the proper setting would be found. Obviously, such a control would require a rather objectionable amount of manipulation.

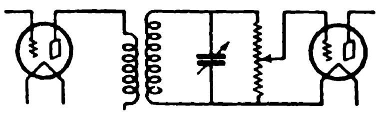
In receivers of this kind, the problem permits of either of two practical solutions. Either the reduction in signal voltage must be accomplished between circuit elements, such as for example between the antenna and first tuned circuit, or between tuned circuits and tubes. This may be accomplished by connecting a simple non-inductive potentiometer, or variable resistance, across one of the circuit elements. The other method consists in providing a control of the amplification of the amplifier tubes. This latter method is used extensively, especially when variable-mu tubes are used as r-f amplifiers, for the amplification factor and mutual conductance of this type of tube can be varied over wide ranges simply by varying the control-grid bias voltage.

At (B) of Fig. 270, a variable resistance of some 100,000 ohms maximum value (depending on the type and number of tubes controlled) is connected in series with the "B" supply of the r-f tubes. This controls the volume by raising or lowering the plate voltage applied to the tube. This system has little to be said in its favor, for as the resistance is changed, the plate current in the tube, as well as the actual voltage applied to the plate is varied. If too low a voltage is applied to a radio-frequency tube, it becomes a detector, and consequently distortion takes place. Also it is difficult to reduce the volume down to very low values, when powerful local stations are being received.

At (A) of Fig. 271, another system somewhat similar to the preceding one is shown, except that in this case a variable resistance of the order of 10,000 ohms is in parallel with the primary of one of the radio-frequency transformers. This gives a smoother control of volume, but in addition to the disadvantages of the previous method, the sharpness of tuning of the secondary of the radio-frequency transformer is reduced unless the resistor has a high value. This is because of the increase of load on the secondary when the primary is partially or totally short circuited by the volume



(A)



(B)

Fig 271—(A) Volume control by means of a potentiometer connected in the plate circuit o an r-f amplifier tube (B) Volume control by means of a potentiometer connecte across the secondary of an r-f transformer

control resistor. If a high value of resistor is used to avoid this shunting effect, th plate voltage of the tube will be reduced considerably.

At (B) of Fig. 271 a volume control potentiometer is connected across one o the tuned circuits of the receiver in such a way that any proportion of the total signa voltage developed across the tuned circuit may be applied to the grid circuit of th amplifier tube. The objection to this is the fact that the shunting effect of the re sistor across the tuned circuit tends to reduce the volume and cause broad tuning. T reduce this it is necessary to use potentiometers having a resistance from ¼ to megohm. The need for such high variable resistances which must be noiseless—

far as possible—and which must vary non-uniformly with respect to angular rotation, prohibits the use of wire-wound resistances, and has led to the extensive use of the graphited-paper type of unit. With the volume control connected across a tuned circuit or its equivalent, the condition should be met that the loading introduced across the tuned circuit should be constant, even though the volume control is varied. This condition obviously eliminated the use of a straight variable resistance across a tuned circuit, for as the volume is gradually reduced a smaller and smaller resistance shunts the tuned circuit, with consequent elimination of the selective and gain properties of the circuit. With the volume control in this position of the circuit, it was there-

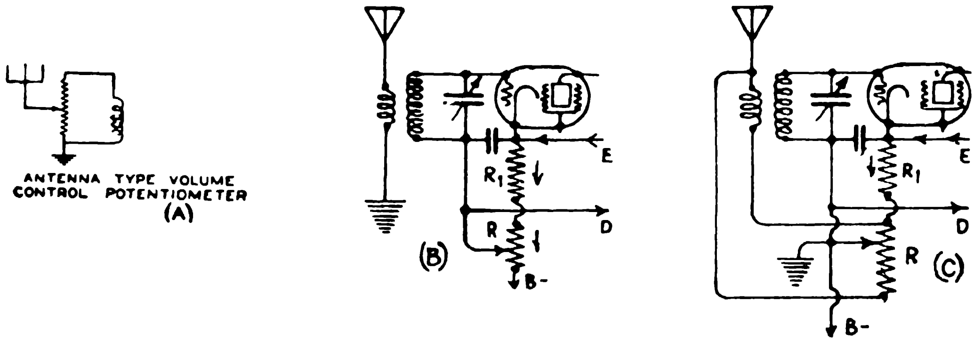


Fig 272—(A) Antenna type volume control (B) and (C)—Volume control by means of variable grid-bias resistor in the cathode circuit of the first r-f tube

fore essential that a potentiometer type of control be used, which imposes a fixed resistance load across the tuned circuit. Another objection to this form of volume control is that all potentiometers have some capacity across their terminals, 8 mmfd. being a real low value for this. This means that besides a resistance being placed across the tuned circuit, a capacity is also added. In the case where a number of tuning condensers are being run from the same shaft, as is the case in single-control receivers, the tuning of this circuit would be thrown out of alignment, and small capacities would have to be placed across all the other variable condensers for exact alignment. Of course, this is not an insurmountable diffioulty, but simply one which is objectionable in quantity production of radio receivers.

In the old forms of receivers using untuned directly-coupled antenna circuits, the volume control shown at (B) of Fig. 267 was quite popular. With this arrangement, a potentiometer of 2,000 ohms or so acted both as the untuned coupling device and the volume control. In receivers using an antenna coupling transformer, the arrangement shown at (A) of Fig. 272 has been extensively used. The potentiometer of about 25,000 ohms resistance, makes it possible to apply any fraction of the total signal voltage induced in the antenna circuit, to the primary of the coupling transformer. This type of volume control is effective only if the receiver is completely shielded so that no signals can be picked up without an aerial. Otherwise, signal voltages from local stations may be set up in the r-f coils and wiring in the set. Obviously, in such cases, the stations will be heard even if the volume control is set at minimum value. Another objection is the fact that when this form of volume control is employed, the ratio of noise to signal may be very great when the volume is turned down. The reason for this will be evident from the following considerations. Noise which appears in the output of a receiver is the result of noise picked up outside the receiver and noise which originates in the receiver proper. The former is independent of the circuit position of the volume control, while the latter is not. Receiver noise, apart from hum, is a combination of tube noise and circuit element noise, and is more or less a fixed quantity for any given receiver. These noises modulate the carrier wave which is present in the receiver, and they therefore show up in the loud speaker output. When volume is adjusted by an antenna control only, the signal amplitude fed into the receiver *input* is reduced, whereas the amplitude of the noise originating

in the receiver is at its full value (since receiver amplification is maintained at its maximum value), and we have a high degree of "noise modulation." If however, a stronger signal is fed into the input of the receiver, and the volume is adjusted by a control located in the radio frequency amplifier beyond the antenna, the relative degree of noise modulation is smaller (since the noise is the same but the signal amplitude is greater); and secondly, the volume adjustment reduces the noise and the signal together, so that the ratio of noise to signal is reduced. It should be noted that the volume control is effective in reducing the noise-signal ratio to the extent that it is removed from the antenna stage, since it is effective in reducing noise (for a given output) originating ahead of it, but not that originating in the parts of the receiver circuit following it. Hence the nearer it is located to the detector circuit the less will be the noise present.

A realization of this fact has led some circuit designers to favor a dual volume control consisting of one part placed in the r-f amplifier circuit and one part in the audio circuit, both being operated from the same shaft. The idea is, that when the volume is reduced by reducing the r-f signal, the audio amplification, noises and hum due to the a-c operation, are also reduced. While this arrangement has many commendable features it has not been generally adopted on account of the increased cost and wiring complications and the fact that since the trend of receiver design is toward greater r-f amplification and less a-f amplification, the advantages gained by the control in the a-f amplifier become less.

When separate-heater screen-grid type r-f amplifier tubes are used, there are several additional methods of controlling volume Volume can be controlled in this type of tube (as it can also in the '27 type tube) by varying the grid bias voltage applied to the r-f tubes as shown in the simplified method at (B) of Fig. 272 By increasing the grid bias voltage (making it more negative), the mutual conductance and therefore the amplification of these tubes is reduced, thereby diminishing the volume. By using this control on the r-f tubes in a receiver, almost complete control of any signal encountered in practice may be obtained. For this purpose, a variable resistor R is used in the cathode-return circuit as shown. If two '224 screen-grid tubes are controlled, R should be about 10,000 ohms If four are controlled it should be about 5,000 ohms, etc. As more resistance is inserted into the circuit by moving the contact arm, the negative grid bias voltage is increased and the amplification factor and mutual conductance are decreased In series with this variable resistor is a fixed resistor R_1 for limiting the minimum bias voltage, (which is the bias value prescribed by the tube

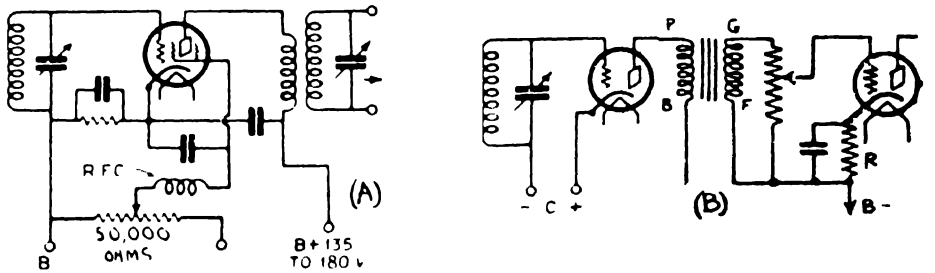


Fig 273—(A) Volume control by screen-grid voltage control obtained by the use of a potentiometer in the screen-grid circuit (B) Volume control in the audio circuit by means of a potentiometer connected across the secondary of the first a-f transformer

manufacturers). If this resistor were omitted, when the volume control resistor was turned to the end at full volume position, no resistance would be in the circuit, the grid bias voltage would be zero and the signal would cause grid current to be drawn by the tube, with resulting distortion and broad tuning. An improvement on this form of volume control is shown at (C). The peculiar connection from the bottom of R to the primary of the antenna coupling transformer helps to give excellent control for very low volumes. As the moving contact on R is moved downward to decrease the volume, a smaller and smaller proportion of the antenna-to-ground voltage is being applied to the primary coil because the slider, (which is connected to ground) is moving toward

the antenna end of resistor R, and therefore the signal *input* to the receiver is reduced. This combination control reduces the antenna pickup enough so that the usual modulation effects due to strong local stations are greatly diminished. A resistor having a tapered variation of resistance should be used for circuits of this kind. If this antenna-shorting action is not desired, the bottom end of R should simply be connected direct to B minus as shown at (B). In both (B) and (C), the wire marked E connects to the cathodes of the other r-f tubes, and wire marked D connects to the grid-return circuits of these tubes.

The volume can also be controlled by varying the screen grid voltage as shown at (A) of Fig. 273 when screen-grid tubes are used. Moving the arm of the potentiometer of 50,000 ohms or so, varies the voltage applied. Either of these last two methods give satisfactory control when ordinary screen-grid tubes are employed, only provided the signal input to the first tube is not too great. For loud signals, such as are produced in the vicinity of local broadcasters, either of these methods is unsatisfactory, not because they do not give complete control, but because distortion is introduced. As the volume is reduced by varying the negative bias, a point is reached at low output where the tube is operated at the lower bend of its E_c - I_p characteristic, and the tube acts as a grid bias detector, producing severe distortion of the signals. This can be corrected only by reducing the input signal to the first r-f tube by means of an antenna volume control, which must necessarily be used in conjunction with the C-bias or screen-voltage adjustment in order that complete control of loud signals may be secured. This requires a double volume control which is of course undesirable.

When variable-mu type screen-grid tubes are employed, the volume control method of (B) of Fig. 272 works very satisfactorily, without the troubles encountered when it is used with ordinary screen-grid tubes. In order to utilize the full volume control range of the '35 or 551 type tube, the volume control resistor should be of such value as to apply a maximum grid bias voltage of approximately 50 volts depending upon the circuit design and operating conditions. It will be remembered that one of the features of this tube is that the mutual conductance and amplification factor for high negative grid bias voltages are very low, (see Fig. 230).

Volume control in audio amplifiers used for public address work or for phonograph-amplifier combinations usually consist of a 500,000 ohm potentiometer connected across the secondary winding of the first audio transformer as shown at (B) of Fig. 273. This provides a smooth volume control since any fraction of the signal voltage induced in the secondary winding may be applied to the grid circuit of the tube.

This resistance will actually tend to improve the tone quality of the receiver, since, if a rather poor transformer is being used, it will smooth out the amplification curve and make it quite flat. This unit should have a maximum resistance of about 500,000 ohms, and should always be placed across the first audio transformer It is then possible, on strong signals, to cut down the volume and prevent overloading of even the first audio tube. However, if the resistance were connected across the second transformer, it would not be possible to prevent overloading of the first tube. Connection across the first transformer is therefore advisable.

The ideal volume control is one which smoothly and uniformly controls the sound emitted from the speaker from a whisper to a maximum intensity. The control should not allow any of the tubes in the set to overload, and in fact it should not change the electrical characteristics of any part of the receiver in any harmful way.

The resistor used must provide a smooth control, so that it can be operated without audible evidence of its use beyond that of changing the volume. There must be no scraping, rustling, or clicking, and at no point must there be a sudden increase or decrease of volume. The change of volume as judged by the ear must, as far as possible, be spread out uniformly over the full range of the control.

376. Automatic volume control: In all of the volume control systems just described, the control must be operated manually by turning

a volume control knob. Automatic volume control systems have been designed for use in radio receivers, in order to reduce the necessity for continual manipulation of the volume control knob. The use of automatic volume control means that once the adjustment for the desired sound output level is made normally, by setting the volume when the loudest local station is being received, tuning the receiver through local and distant stations will not produce sudden loud blasts of sounds when tuning in the carrier wave of a strong station. If the distant station is much weaker than the local station, so that the maximum amplification of the receiver will bring the signals up to the necessary strength, the station will be heard at the desired volume level, otherwise it will be heard faintly. The very weak stations are not brought up to the volume of the strong one unless the receiver is capable of amplifying their signals enough to bring them up to this level. This is an important point to remember. In this sensitive condition, the receiver will of course greatly amplify all stray electrical disturbances that may come in with the signal and noisy reception may result.

In receiving programs from certain stations, "fading" causes a great deal of annoyance. With good automatic volume control, the receiver sensitivity is shifted simultaneously with the received field strength of the transmitter, so as to maintain a constant output level. The disadvantage of course, is that the "noise" output due to stray electrical disturbances which may also be received, remains constant.

One automatic volume control system which has been used, employs a two-element detector tube whose direct current component of plate current is made to flow through a resistor and the voltage drop thereby obtained is made to vary the grid bias applied to the r-f amplifier tubes and so vary the amplification, (see latter part of Art. 313). The audio-frequency variations in the detector plate current are filtered out from the steady direct current. A stronger signal strength tends to increase this direct current. This changes the voltage drop across the resistor, thus changing the bias voltage applied to the control-grid circuits of the r-f tubes so as to decrease the amplification (see explanation referring to (B) and (C) of Fig. 272).

A simple automatic volume control arrangement devised by Mr. A. C. Mathews, Jr. and which can be used on existing receivers employing '24 type screen-grid tubes is shown at (A) of Fig. 274. This employs a '27 type tube whose function is to automatically vary the *screen grid* voltage applied to the '24 type tubes used in the r-f amplifier. It is connected to the receiver by simply breaking the screen-grid voltage supply lead at the r-f tubes and connecting the lower wire to the screen-grid instead. The top wire is tapped on to the grid of the detector tube.

In order to properly control the volume, the screen grid potential must be made variable over a considerable range. Manual variation under this system is achieved by adjusting the bias of the volume control tube by means of the 50,000-ohm potentiometer provided. The plate current passing through the resistance in the plate circuit provides the necessary drop to vary the voltage over the required range. The voltage on the screen grids, and in consequence the volume, is thereby reduced. A signal applied to the grid of the control tube reduces the bias and consequently increases the plate current, providing an automatic decrease in gain. The constants of the circuit must be so proportioned as to function rapidly—but the electrical inertia must still be great enough to avoid any possibility of "swamping out" low-frequency modulations, as these are slow changes in the amplitude of the signal. Since the volume-control tube must have its plate at the same potential as the screen-grids of the r-f amplifier it is necessary, in order to obtain the correct plate voltage on the '27 volume-contro tube, to take off-voltage taps at —60 and —80 volts on the power-supply unit. This put a potential of approximately 135 volts on the plate with respect to the cathode.

Since it is rather difficult with a system of this kind to know when the receiver is tuned exactly to resonance, because the volume seems the same over several divisions of the dial, a 0-5 d-c milliammeter is usually included in series with the plate of the volume control tube, so as to give visual evidence of the resonance point, by a maximum deflection of the pointer. In a commercial receiver of this design a shunt across the speaker terminals is used while tuning, so that the volume is reduced to a mere whisper. With the meter to indicate whether the circuits are in resonance with the carrier, the speaker gives evidence as to whether that carrier is modulated, for the meter will show a reading on the unmodulated carrier. This enables the person operating the receiver to tune the set exactly to the desired carrier, even if it is at an extremely low output level.

At (B) of Fig. 274 a different version of an automatic sensitivity

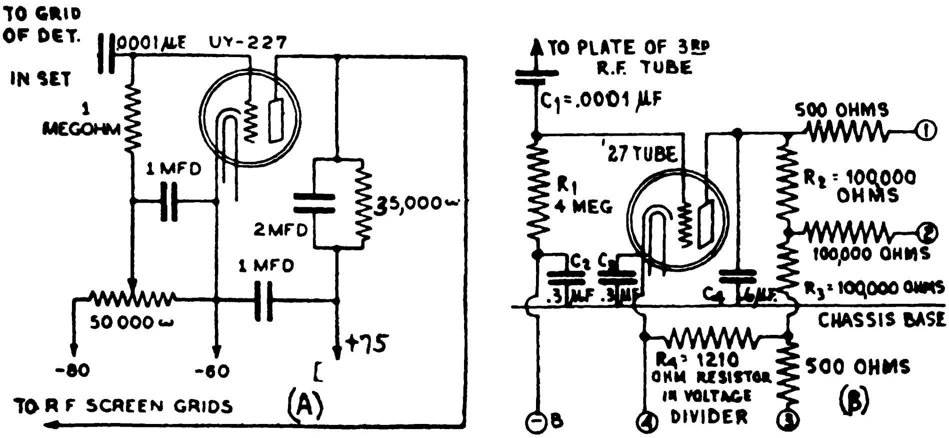


Fig. 274—(A) Automatic volume control system for screen-grid receivers An additional '27 type tube is used. (B) System used on Stromberg Carlson models 12 and 14 screen-grid receivers.

control is shown. This is a simplified diagram of that used in the Stromberg-Carlson models 12 and 14 receivers, in connection with the 3-stage t. r. f. screen-grid amplifier employed in them.

In this the control tube is a 227, the grid of which is connected through a 0.0001 mfd. condenser to the plate of the third radio-frequency tube, which is a 224 screen grid tube. The grid return is connected to B minus, the most negative point in the circuit, and the cathode (4) is connected to a point on the voltage divider which is positive with respect to B-minus, but negative with respect to ground. The voltage between B minus and (4) is the steady bias on the control tube, which makes it a grid-bias or plate-bend detector.

The signal voltage impressed on the grid varies the direct current component in the plate circuit of the control tube and the drop in the resistors R2 and R3. Point (1) is connected to the grid return of the first screen grid radio-frequency amplifier, point (2) to the grid return of the second, and point (3) to the grid return of the third tube. It is only the bias on the first two 224 type r-f tubes that is varied automatically, the first by the amount of drop in the two resistors R2 and R3 and the second by the amount of drop in R3 alone. Thus the degree of control varies for the two tubes, being greater for the first tube than for the second. This is called "tapering of the bias."

A condenser C4 of 0.6 mfd. is connected across the plate circuit of the control tube to filter the carrier from the direct current component. Other by-pass condensers to aid in the filtering are C2 and C3, each of which has a value of 0.3 mfd.

The resistors of 500 and 100,000 ohms in the leads to the r-f tubes, are included to suppress any oscillations which might be set up in them. Terminal (1) connects to the grid return of the first r-f amplifier tube; (2) connects to the grid return of the second radio frequency amplifier tube; (3) connects to a point on the voltage

divider 3 volts negative with respect to the chassis and the ground. The resistance between (3) and ground is 100 ohms and is in the main voltage divider; (4) connects to a point 1,210 ohms below (3) on the main voltage divider; (B–) connects to the negative side of the B supply circuit, which is separated from (4) by 260 ohms.

A point to observe in this control arrangement is that the most negative point of the B-power supply unit is not grounded as is customary, but the ground is placed at a point 1,750 ohms higher up. This is done so as to get the proper voltages on the control tube with reference to the voltages applied to the tubes in the amplifier.

The voltage between any two taps depends, of course, on the current taken from the various taps, and the circuit is not applicable without suitable change to any receiver. The receiver in question contains three 224 screen grid radio-frequency amplifiers, one plate-bend 227, high signal detector, one 227 audio-frequency amplifier, and two 245 power amplifiers in push-pull, transformer coupling being used throughout the audio amplifier. A milliammeter connected in the cathode circuit of the secondary r-f tube acts as a visual tuning meter as described for the previous system. This type of control gives excellent signal input voltage. The output remains practically constant at 100 arbitrary units between inputs from 100 to 5,000 microvolts. Below 100 microvolts the output drops rapidly and therefore 100 microvolts has been set as the input at which the control tube "takes hold." At 5,000 microvolts the output begins to rise rapidly as the input increases, but even at 10,000 microvolts the output has not yet doubled.

The advantage of the automatic feature is obvious. A signal of 100 microvolts is a very weak signal and one of 10,000 microvolts is a comparatively strong signal. Yet the variation in the output does not vary as much as 2 to 1. If the normal signal intensity of a station is around 2,000 microvolts, there is practically no variation in the output even if the input falls as low as 100 microvolts and rises as high as 5,000. Fading under these conditions will practically be absent and the only effect that the fluctuations would have on the received signals would be a rise and fall in the proportion of stray noises, (rising as the signal faded out and falling as it came back).

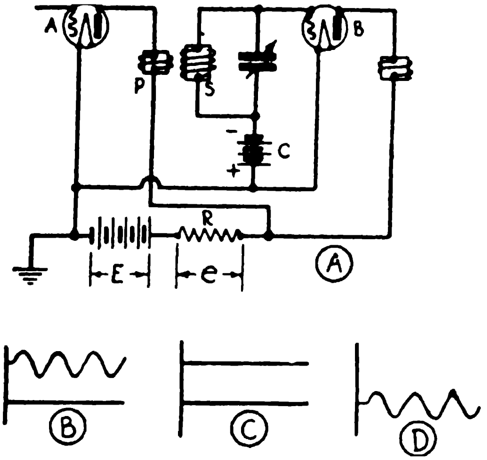
It is evident that the automatic volume control feature in a receiver is much more effective if variable-mu (super-control) type tubes are used in the r-f or i-f amplifier than if ordinary screen grid tubes are employed (see Art. 313).

377. Coupling in the "B" supply: When a receiver utilizes a single source of plate voltage for more than one stage (as is almost always the case) coupling between stages may take place through the resistance of this voltage source, as shown in (A) of Fig. 275. New "B" batteries have a very low internal resistance, but when they become old and discharged their internal resistance may increase to as much as 1,000 ohms. This is due to resistance of the active material between the zinc cylinder and carbon rod of each of the small dry cell units. In a 45-volt "B" battery there are 30 of these cell units connected in series, so the total internal resistance is equal to 30 times the resistance of each unit. Layerbilt batteries have a much lower resistance due to the wider cross-sectional area of the active material.

"B" power supply units used in electrically operated receivers, all use some form of resistance for a voltage dividing device, and the plate currents of the various tubes must flow through this resistance, which often amounts to several thousand ohms (see Articles 509 to 511). In either case the internal resistance may be considered as a resistance R in series with the power supply device (here shown as batteries for simplicity).

The resistance R is included in the common plate circuit of both tubes A and B. It should be remembered that R is really in the "B" voltage supply unit but it is shown outside for simplicity in the diagram. The plate current of either of the tubes varies somewhat in the manner shown at (B) due to the signal. This is a varying current flowing in one direction. This varying plate current flowing through R will produce a varying

voltage drop *e* across it. The effective voltage acting on the plate at any instant is equal to the *e. m. f.* of the "B" voltage supply minus the voltage drop due to its internal resistance, that is, E — e. Therefore the effective plate voltage applied to the tubes is also varying, thereby varying the plate current. The varying plate current of tube B, when flowing through R produces a varying voltage drop across R which causes variations in the plate current of tube A. These are transferred to the secondary S, by the primary P, and are therefore re-impressed on the grid circuit of tube



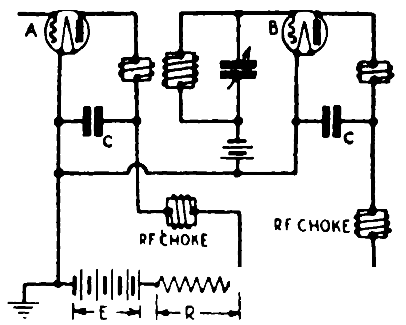


Fig 275—How interstage coupling may occur in the common impedance of the "B" power supply unit It may be prevented by means of the choke coils and by-pass condensers shown at (E)

B. In other words, signal-variations in the plate circuit are re-impressed on the grid circuit and are re-amplified. *Regeneration* is thereby produced. If the coupling resistor R is large enough and the circuit losses are low enough, the tube may act as an oscillator thus interfering with reception. The same action occurs among the various other tubes in the receiver. Also in screen-grid tubes, since the positive screen-grid voltage is also obtained from the "B" power supply unit, coupling of this kind can also take place in the screen grid circuit.

Obviously the cure for this interstage coupling is to eliminate the pulsations in the current flowing through the "B" power device E. This is accomplished by the simple low-pass filter arrangement shown at (E), where an r-f choke coil is connected in each plate lead, and a by-pass condenser C connects around to the B – side or cathode of the circuit. Since the action is the same as has already been described for the choke and condenser filter connected in the plate circuit of a detector, this will not be considered again. The condenser merely acts to smooth out the variations in the current flowing through the "B" power unit, thereby preventing the *varying* coupling.

R-F chokes for this purpose are usually of about 85 millihenry size, as shown at the right of Fig. 124. In r-f circuits, by-pass condensers of from .2 to .5 mf. are commonly employed. Condensers for this purpose are shown in Fig. 276.

In order to serve as an efficient by-pass to prevent undesirable coupling, the impedance offered by a condenser to currents of any given frequency must be considerably lower than the impedance of the apparatus around which it is desired to by-pass the current.

For most efficient operation, it is important that the by-pass condenser be connected as close to the points between which the current is to be by-passed as possible. While the use of by-pass blocks which include two or more condensers in one unit is economical in by-passing several circuits or circuit branches, this method should only be used when the circuits which are to be by-passed are close together so that long leads are not required to connect the condensers across the points to be by-passed. In general, better results will be obtained if individual by-pass condensers are connected *directly* across the terminals to be by-passed.

In audio circuits the same action may take place. The use of a filter in the plate circuit also helps here. The size of the chokes and condensers employed must of course be larger, since the frequency of the pulsations is much lower than in r-f circuits.

In general, common coupling in the B– power supply unit is more serious in receivers designed for high amplification per stage than in others, because any stray varying voltage getting back into a previous stage is amplified greatly and may cause the entire circuit to oscillate.

378. Automatic tuning and remote control: Automatic tuning of radio receivers either by rotating selector dials or by push-buttons or levers, has been accomplished by several systems which are in use. These are of two general types—those in which a separate lever is provided for selecting each station which the receiver has previously been adjusted to receive; and those in which a selector dial controls the tuning to any point on the dial. In both systems, the tuning condensers are rotated by an electric motor to the exact position required for reception of the station. In the former, the number of stations which may be received depends on the number of plungers provided, although additional stations may be brought in at points in-between by means of an ordinary tuning dial provided. In the latter, any number of stations (within the range of the receiver) may be tuned in at any point on the dial at will. These systems have not become generally popular for use in homes, due to their complications and cost. Midget type receivers are so inexpensive that it has been found more practical to use several such receivers in a home in which it is desired to provide radio reception in several rooms. These provide the

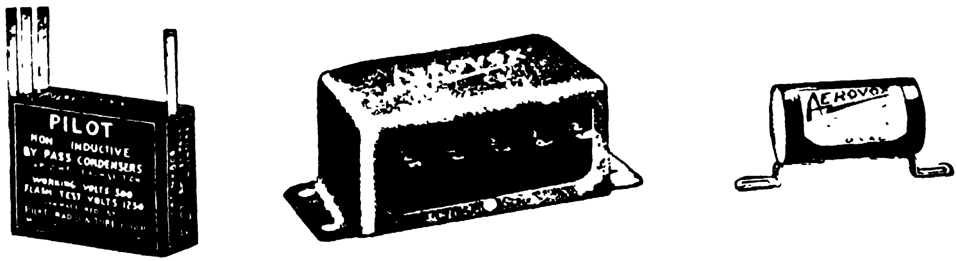


Fig 276--Several by-pass condensers used in radio receivers Left 3-section condenser, each section is 2 mf Middle 4-section condenser with common terminal Right: Compact, tubular form of by-pass condenser made in sizes from .01 to .1 mf.

added advantage that different programs may be received on the different sets in the various rooms at one time.

379. The superheterodyne receiver: While the superheterodyne tuner may be properly classed as a special form of radio-frequency amplifier system, it will be considered separately in the next chapter on account of its special circuit features and importance. Then, in the following chapter the design of inductance coils, tuned circuits, and shielding methods will be studied.

REVIEW QUESTIONS

1. What is meant by the term "radio-frequency amplification?"
2. Why is r-f amplification used in most modern radio receivers? What other form of amplification could be used?
3. What factors determine how much r-f amplification is required in a receiver?
4. State and discuss the requirements of a radio receiver for receiving broadcasted programs, for home entertainment.
5. What is meant by the term (a) microvolts per meter, (b) field strength?
6. What signal strength in microvolts-per-meter is required at the receiving antenna for year-round high-class reception?
7. An antenna 100 feet high has induced in it a signal voltage of 30 microvolts. What is the strength of the field surrounding the antenna?
8. Draw an outline diagram of the main parts of a simple t-r-f. receiver system and explain the advantages and disadvantages of the system.
9. Repeat question 8 for a receiver employing a band selector followed by several stages of untuned r-f amplification.
10. Explain (with diagrams) three methods of coupling successive amplifier tubes in t-r-f amplifiers and discuss the advantages and disadvantages of each.
11. Why is the variable-mu tube considered such an excellent r-f amplifier?
12. Since the resistance-coupled amplifier is so simple and inexpensive, why is it not used in r-f amplifiers?
13. Draw a circuit sketch illustrating the use of parallel-feed plate supply in the plate circuit of an r-f amplifier tube. What are its advantages?
14. Explain why the use of several similar tuning circuits in a receiver increases the selectivity.
15. Why is a straight-sided square-topped tuning response desirable in radio receivers?
16. Explain the operation of one form of band-pass tuner or "band selector"
17. What is the effect on the width of the band passed, as the frequency is increased in a band selector using (a) capacity coupling; (b) inductive coupling?
18. Explain in detail what is meant by cross modulation, and how it may be produced. What are its effects? What must be the form of the E_g - I_p characteristic of a tube which produces severe cross modulation effects. What must be the form for one which does not produce them. What type of tube fulfills (a) the first condition; (b) the second condition?

19. What is a S. L. C.; S. L. W.; S. L. F.; Centraline frequency, condenser?
20. How is single-dial tuning control obtained in receivers employing a number of tuned stages of r-f amplification?
21. What is a gang condenser? What is a compensating condenser and what is it used for?
22. How may the tuned circuits in a single control receiver be matched practically?
23. Why must the tuned circuits in a single control receiver be matched exactly? What happens if they are not matched exactly?
24. What is the reason for slitting one of the end plates in each section of a gang condenser?
25. What effect does the antenna have on the tuning of the first condenser of a receiver employing a tightly coupled antenna coupling transformer? How may this effect be reduced by changing the design of the transformer?
26. Why is a volume control used in radio receivers? What is the difference between a manually operated volume control and an automatic volume control?
27. Draw circuit diagrams for five types of volume controls which have been used in radio receivers, and explain the operation, advantages and disadvantages of each type.
28. Draw a desirable volume control circuit for a t-r-f receiver employing three variable-mu screen-grid r-f tubes.
29. What are the relative advantages of (a) placing the volume control ahead of the detector; (b) placing it after the detector?
30. Explain how coupling between amplifier stages can take place in the "B" power supply unit and how it may be eliminated. Why is it objectionable?

Chapter 22

SUPERHETERODYNE RECEIVERS

REVIEW OF T-R-F SYSTEM — THE SUPERHETERODYNE SYSTEM — ADVANTAGES OF THE SUPERHETERODYNE SYSTEM — "BEAT FREQUENCIES" — THE "BEAT" ACTION IN A SUPERHETERODYNE — THE R-F AMPLIFIER IN THE SUPER — IMAGE FREQUENCY — DESIGN OF THE R-F AMPLIFIER — THE OSCILLATOR — SINGLE CONTROL OF THE TUNING CIRCUIT — CHOICE OF THE INTERMEDIATE FREQUENCY — THE INTERMEDIATE AMPLIFIER — THE SECOND DETECTOR — "REPEAT" POINTS — THE "AUTODYNE" — FREQUENCY CHANGERS — ADJUSTING THE CIRCUITS OF A SUPERHETERODYNE — REVIEW QUESTIONS.

380. Review of t-r-f system: In the tuned radio-frequency amplifier system, which we studied in Chapter 21, a number of tuned amplifier stages are adjusted, usually by a single dial, to the different frequencies of the stations it is desired to receive. Considering receivers of this type designed to work on the usual broadcast band, it is evident that the tuned circuits are so designed that they may be adjusted to tune to any frequency between 1500 kc (200 meters) and about 545 kc (500 meters). The signal voltage is induced in the antenna circuit; is then amplified by the r-f amplifier; is detected or demodulated (changed to audio-frequency); and is finally amplified further by one or two stages of audio amplification, the output from the audio amplifier supplying the loud speaker. This system is shown in simplified form at (A) and (B) of Fig. 245. It is important to remember that in the t-r-f amplifier system the signal is amplified *at its own carrier frequency.* It is difficult to design a receiver of this kind to give high amplification, perfect selectivity and ideal fidelity of reproduction. Due to the high frequencies of the signal voltages being amplified, it is difficult to obtain amplifications of more than 40 or 50 per stage even when screen grid tubes are employed. This necessitates the use of many stages, if high sensitivity is to be obtained. Also since the primary of each r-f transformer induces a higher voltage into the secondary at the higher frequencies than at the lower ones, due to the more rapidly varying magnetic field, the r-f amplification is not uniform over the entire broadcast band unless special circuit arrangements for constant coupling are employed. These have not yet been developed to a point where they are simple, inexpensive and generally satisfactory. Also, in order to obtain a satisfactory r-f tuning curve consistent with adequate selectivity, band-pass tuning circuits must be employed (see Fig.

257). Since these band-pass circuits must be of the variable tunable type, tunable to any frequency in the frequency range the receiver is to cover, they cannot be built with as great efficiency as they would have if designed to work at one single frequency. This brief summary of the operating features of t-r-f receivers will enable us to better appreciate and understand the advantages of the superheterodyne circuit.

381. The superheterodyne system: In the superheterodyne circuit, instead of selecting and amplifying the signal at its own particular

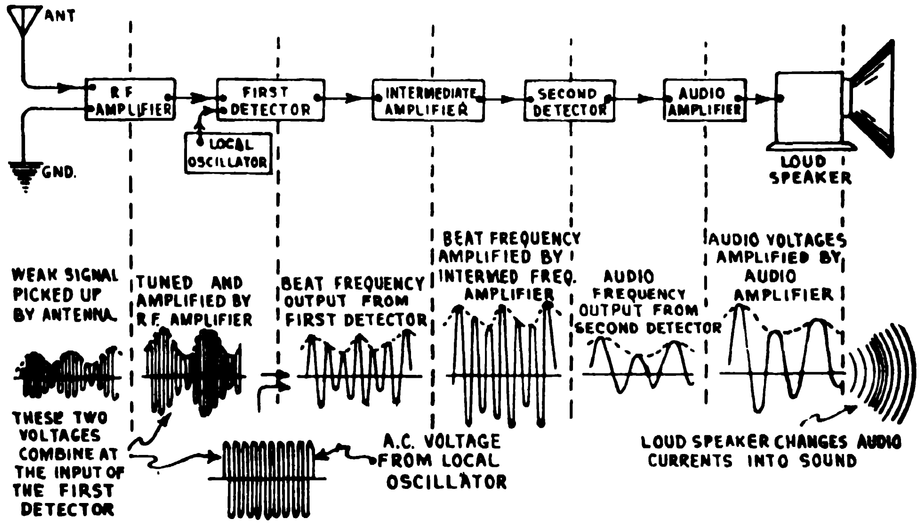


Fig. 277—Functional diagram of the various parts of a superheterodyne receiver showing the changes which occur in the signal voltage in each part of the receiver. The weak signal voltage induced in the antenna circuit is tuned and amplified, combined with the output from the oscillator, demodulated, amplified and tuned again, demodulated again, amplified again at audio frequency, and then reaches the loud speaker, which converts it into sound waves

carrier frequency (which is a high frequency) by means of circuits which must be adjusted to that particular frequency, the high carrier frequency is changed to a lower fixed frequency, so it can be amplified and the signals of unwanted stations eliminated much more efficiently. The fixed frequency at which the signals are amplified is usually called the *intermediate frequency* sometimes abbreviated "i-f". Probably the single greatest difference between the t-r-f amplifier system and this one, is that in the former the receiver is tuned to the frequency of the signal and the signal is amplified at that frequency, while in the superheterodyne, the signal is tuned in and then changed in frequency to the lower value to which the intermediate amplifier is "fixed-tuned", and is amplified at that frequency.

The main parts of a superheterodyne receiver and the changes which the r-f signal undergoes are shown in Fig. 277. The fields of many stations induce modulated r-f voltages in the antenna circuit. The signal of the unwanted stations are usually tuned out or separated somewhat from that

of the wanted station by the antenna tuning circuits, and the latter is amplified by a stage of tuned r-f amplification. Then it is fed to the mixer circuit, where it is "mixed" or combined with a *steady* signal of a definite frequency generated by the "local oscillator" tube. This operates at a frequency differing from the signal frequency by an amount equal to the fixed frequency of the intermediate amplifier. After passing through the first detector, this produces a resulting beat frequency voltage having the same frequency as that to which the intermediate amplifier is tuned, and essentially equivalent in modulation to that of the original signal frequency. This single frequency modulated voltage is then amplified by the intermediate amplifier, then fed to the detector where it is demodulated or changed to audio frequency, is amplified further at audio frequency by the a-f amplifier, and finally fed to the loud speaker. The use of an r-f amplifier stage ahead of the first detector tube is not essential to the operation of the superheterodyne receiver, but it is used for several special reasons in modern supers as we shall see. We will now proceed to a detailed study of the operation of the various parts of the receiver.

382. Advantages of the superheterodyne system: The superheterodyne tuner possesses two advantages which the t-r-f type of tuner can never possess. One is the fact that in the super, so called "arithmetical" selectivity is obtained during the heterodyning of the incoming signal with the local-oscillator signal. This will be explained later. Also, the amplifying is done at the comparatively low fixed-frequency to which the intermediate amplifier is tuned (excepting the amplification obtained in the r-f amplifier stage ahead of the first detector tube). Since this is usually around 460 kc in modern superheterodynes, each intermediate amplifier stage can easily be made to produce an amplification of about 60 to 80, when screen grid type tubes are employed. Contrast this with the amplification of about 40 per stage usually obtained when the amplification is carried out at the high frequencies (1500 kc. to 545 kc.) at which the signals are amplified in the ordinary t-r-f receiver. This is because of the serious effects of stray and tube capacitances at these high frequencies.

However, it should be understood that t-r-f receivers can be built to be just as sensitive as superheterodynes. It is just a question of providing enough amplifier stages. The point is, that in the superheterodyne system the same sensitivity or amplification can be produced with *less* amplifier stages.

Also, since the intermediate amplifier stages in the super operate at the one *fixed* "intermediate frequency," it is possible to use band-pass tuning in them, of a form designed to have much more nearly the ideal straight-sided flat-topped tuning characteristic desired, than is possible where the band-pass tuner must be tunable to various frequencies over a wide frequency range as in the case of the t-r-f receiver. This means that in a well designed superheterodyne it is relatively easier to obtain the high degree of selectivity required in receivers for use under present congested conditions. While these are possibly the most important ad-

vantages of the superheterodyne, others will be pointed out as we proceed with our study.

383. "Beat" frequencies: Since the superheterodyne receiver depends for its operation on the production of "beat" frequencies, it is essential that we understand this action first. The phenomenon of the production of "beat frequencies" in electrical circuits is somewhat similar to the production of "beats" or beat frequencies, with sound waves.

Suppose we strike the note C in the bass of a piano, we hear a certain note due to this particular frequency of vibration. Now if we strike one of the adjoining keys,

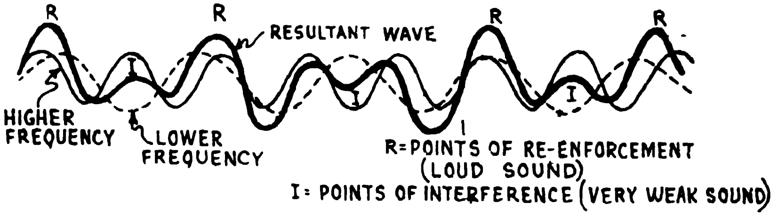


Fig 278—Phenomenon of "beats," produced by the combination of sound waves of slightly different frequencies. The two light curves represent sets of simple sound waves having a vibration frequency ratio of 8 to 5. The heavy curve, represents the resultant sound wave obtained by adding the amplitudes of the individual curves together at various points, due regard being taken of the relative directions at these instants. Four points (R) of reinforcement (*beats*) and three of interference (I) are produced

we hear a different note. If we strike both together, a note which differs slightly from both of these will be heard, and the sound will be found to swell and diminish at regular intervals. At regular intervals the two separate sound waves are in such phase relation that a condensation of one combines with a condensation of the other, reënforcing it and producing a louder sound or "beat note". At intermediate instants, condensations combine with rarefactions and their interference produces weak or even inaudible sounds. Hence, the effect is a succession of loud sounds called *beats*, separated by intervals of relative silence as shown in Fig. 278. Such beat notes can be produced by any two musical instruments when notes differing slightly in frequency are played. The number of beats produced per second will equal the difference in frequency of the two sets of vibrations. Thus with two sounds having frequencies of 256 and 260 vibrations per second respectively, four beats will be produced every second.

Now let us consider the production of "beat frequencies" in electrical circuits. Whenever two voltages or currents of different frequencies are combined, periodic reinforcement and weakening of the voltage or current are produced. Let us see just how this happens.

Let us suppose that we have an a-c generator producing voltage or current of a frequency of 10 cycles, rising and falling during one second as shown at (A) of Fig. 279. Let us suppose that we have another a-c generator producing another a-c voltage or current of 8 cycles, rising and falling during one second as shown at (B). We will assume that they are both introduced into a common "mixer" circuit as at (E), say by electromagnetic induction between the primaries and secondaries of the two transformers L and M shown. At the instant represented by the vertical line 1 - 1 the 10 cycle voltage induced in coil L is at its peak value, and in the positive direction. At the same instant, the 8 cycle voltage induced in coil M is almost at peak value in the opposite direction (negative) as shown. If we assume for simplicity that the peak value of the 10 cycle voltage is slightly greater than that of the 8 cycle voltage, then a small net voltage in the positive direction, equal to the difference between these peak values, acts in the "mixer" circuit at that instant as shown by the height of the "combined voltage" wave above the axis line O - O at (C) where 1 - 1 crosses it. Thus at each instant the voltages induced in L and M combine (with regard to their direc-

tions at the instant) to produce a resulting voltage equal in value to the algebraic sum of their individual values. At the instant represented by 2 - 2, the negative voltage of the 10 cycle current and the negative voltage of the 8 cycle current have combined with each other to form a much stronger negative voltage amplitude in the combined curve at (C). At the instant represented by vertical line 3 - 3, the positive voltage peaks of the two upper frequencies have combined to form a new positive peak of much greater positive amplitude as shown at (C), etc. Now, close study of the curve at (C) reveals that between the instants represented by 1 - 1 and 3 - 3, the various *peak values* of the *combined voltage* rise steadily from a minimum to a maximum value. Then from instant 3 - 3 to 4 - 4, the peak values of the

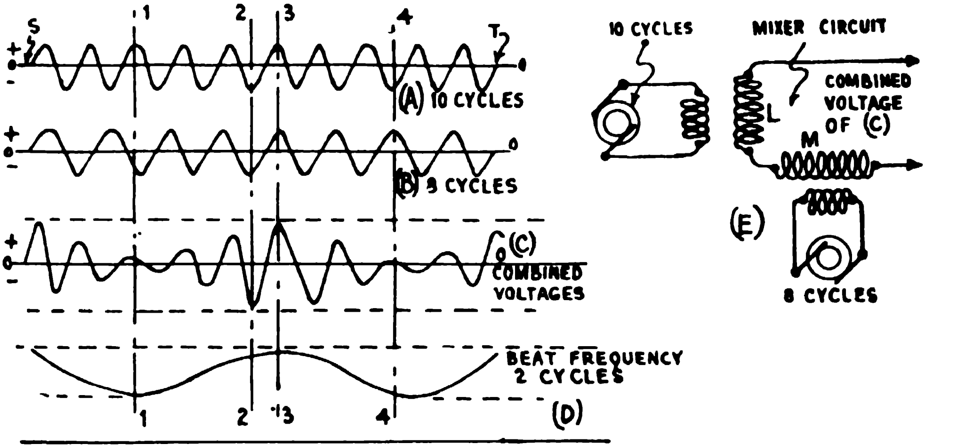


Fig 279—The production of a "beat frequency" (D) in an electrical circuit, by the combination of two currents or voltages (A) & (B) of differing frequencies The "beat frequency" is equal to the difference between the frequencies of the two voltages or currents which have been combined

combined voltage fall steadily to a minimum value again. This rise and fall in *amplitude* of the *peak values* is represented by the curve at (D). Curves (A) and (B) are drawn to scale, that is, during the interval from S to T, there are 10 waves or cycles at (A) and 8 waves or cycles at (B). We find that during this time there are 2 waves or cycles produced at (C), that is, the new resulting current or voltage produced (shown at (C), varies in "amplitude", *the cyclic variation of its amplitude* taking place at a frequency equal to the *difference* between the two original frequencies at (A) and (B). This point is a very important one to remember, for it is a condition which has been confused somewhat by loose consideration of the subject of beats by some writers.

There is one additional important point to understand here. Referring back to Fig. 279, and by actually counting the number of cycles at (A), (B), and (C) we find that during the time the current or voltage at (A) goes through 10 cycles, that at (B) goes through 8 cycles, and that at (C) goes through *9 cycles*. In other words, when two voltages or currents are combined, what we really get, is a current or voltage having a *resultant frequency which is the average of the two frequencies*. This resulting current or voltage however, varies in *amplitude*, the cycle of its *amplitude variations* taking place at a frequency equal to the difference between the two original frequencies. In the diagrams in Fig. 279 simple sine-wave voltages or currents were considered in order to make both the illustrations and the action easy to understand. If one of the voltages or currents considered were modulated, the same action would take place, only in this case, the amplitude of (C) would be modulated by this modulation at each instant. Its *peak* values would vary at the difference in frequency, but would not vary in simple sine-wave form as shown at (D). They would vary according to the modulation of this one wave. This is too complex to be shown in a simple diagram.

384. The "beat" action in a superheterodyne: An actual example of the "beat" action in a superheterodyne receiver will be considered now. Suppose the modulated carrier signal voltage of a broadcasting station transmitting on say 1,000 kc is being received. Let us further suppose that this was modulated by a 3,000 cycle sound in the broadcasting station. Let us suppose also that the intermediate-frequency amplifier of this superheterodyne receiver is designed to amplify at a fixed frequency of 175 kc, permitting of course, a band of frequencies 10 kc wide (170 kc to 180 kc) to pass through it freely, so that the sideband frequencies will not be cut or weakened. We will forget about the sideband frequencies for a moment and consider simply the carrier frequency. Now the desired signal is separated from those of other stations by the r-f tuning circuit, and is amplified by the single r-f stage. From here it goes to the "mixer" circuit where it is combined with a steady a-c voltage of 1175 kc produced by the oscillator tube in the receiver. (The oscillator has been adjusted to generate a voltage of this frequency for this particular case. When receiving stations of other frequencies, the oscillator must generate a different frequency in order to produce the 175 kc beats). The result is, that in the mixer circuit the 1,000 kc modulated signal voltage and the 1175 kc oscillator voltage combine to produce a resultant voltage having a frequency equal to the average of these, that is 1087.5 kc. This new resulting voltage makes cyclic variations in amplitude, at a rate of 1175 − 1000, or 175 kc every second (beat frequency). These variations in amplitude are in exact accordance with the modulations of the incoming signal voltage. Now this 1087.5 kc resulting voltage is applied to the grid circuit of the first detector tube, this being either of the "grid leak and condenser" type, or the "grid-bias" type. The effect of the detector, is to demodulate the 1087.5 kc voltage, removing the 1087.5 kc variations by the detector action (see Figs. 236 and 237). The output of the first detector is therefore a current or voltage possessing the 175 kc cyclic variations modulated in accordance with the original signal modulations. After passing through the primary of the first coupling transformer, this is an a-c voltage of 175 kc modulated as above. It is then amplified by the intermediate amplifier, and finally fed to the second detector where it is demodulated again, only this time, the 175 kc variations are removed and the audio-frequency modulations are left. These are amplified by the audio amplifier and fed to the loud speaker. The various changes which the incoming signal undergoes are shown at Fig. 277. It is interesting to note that the first detector really performs the function of detection or demodulation, notwithstanding the assertions of some writers to the contrary. It removes the variations of the *average* frequency resulting from the mixing of the incoming signal frequency and the oscillator frequency, and preserves the beat modulation. The second detector removes the intermediate-frequency variations, leaving only the original audio-frequency modulations. Without the first detector, we would have simply the radio-frequency of 1087.5 cycles fed to the in-

termediate amplifier. In this case, just as without the second detector, we would have in the audio circuit the frequency which passes through the intermediate amplifier. Now that we understand the most important action in the superheterodyne, let us proceed to study the design and operation of the various main parts, starting at the antenna circuit and proceeding through to the audio amplifier.

385. The r-f amplifier in the super: Some superheterodynes are designed with sufficient amplification so that their signal voltages may be taken from a small loop of wire. As the loop is directional, it must be turned so its plane points toward the station being received, in order to obtain maximum signal strength. Most supers of recent design are made sensitive enough to operate from a very short antenna, thus reducing the pickup of static, etc. The use of ordinary radio-frequency amplification ahead of the first detector of a super may seem rather inconsistent at first thought, when we remember that so much more amplification would be obtained by using an additional intermediate-amplifier stage instead. The r-f amplifier stage has two other purposes however, besides that of mere amplification. First, it is usually included in order to be able to reduce the strength of the incoming signals of powerful unwanted local stations before they reach the detector, to a value sufficiently low so that they do not produce cross modulation effects on weaker incoming signals which it may be desired to receive. This is the usual problem of "adjacent channel" selectivity which is also encountered in ordinary t-r-f receivers. The other reason for the use of r-f amplifier stage, is one peculiar to the superheterodyne circuit only. This is the problem of eliminating "image frequency".

386. Image frequency: The problem of eliminating image frequency effect is probably the most serious drawback of the superheterodyne system. This is caused by the following action. Since the frequency of the beats produced, is equal to the difference between the frequency of the carrier wave of the incoming signal and the frequency of the oscillator, it is evident that for any one oscillator frequency setting, there is a frequency above this and one below this such that the difference between it and the oscillator frequency is the same.

Suppose the intermediate amplifier is designed for a frequency of 175 kc and a 1000 kc signal is to be received. In order to change the carrier frequency of this signal to the 175 kc intermediate-frequency, the oscillator can be set either at 1175 kc or 825 kc, for in either case the difference in frequency is the 175 kc desired. If it is set at 1175 kc then it will not only change the 1,000 kc signal so it becomes 175 kc in the intermediate amplifier but will also change any 1350 kc signal which may be received, so it also becomes 175 kc in the amplifier, since 1350 minus 1175 is also equal to 175 kc. Therefore, both of these signals will be amplified by the intermediate amplifier and of course will be heard together. The same action would take place if the oscillator were set at 825 kc. In this case, both the 1,000 kc signal and the 650 kc signal would be present in the intermediate amplifier together, after having been acted on by the oscillator voltage and passed through the first detector. In the first case, the signal of 1350 kc is the *image frequency* signal. In the latter case, the 650 kc is the *image frequency*. It is also possible for two signals in the broadcast band, which are separated by the frequency of the intermediate amplifier, to reach

the first detector, one serving to heterodyne the other to this frequency, and a modulation of one or both stations appearing at the loud speaker. This incoming signal of 1, 500 kc could heterodyne with an incoming signal of 1,325 kc to produce beats at 175 kc.

387. Design of the r-f amplifier: It is evident that both of these problems connected with "image frequency" could be solved if we could see to it that only the incoming signal which we desire to receive, gets to the grid circuit of the first detector. This problem has been successfully solved

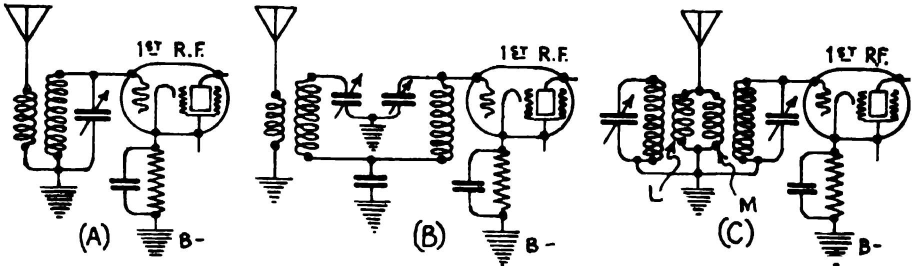


Fig 280—Several antenna circuit tuning arrangements for superheterodyne receivers (see Fig 281)

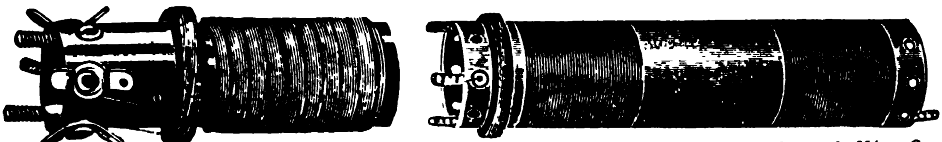
in recent superheterodyne receivers, by obtaining a high degree of selectivity before the first detector through the use of a tuned r-f amplifier stage. For practical reception, it is necessary that this selectivity be such as to reduce the intensity of the interfering signal appearing at the first detector to a point where it is only one-five-thousandth or less of that of the wanted signal. Thus, the tuned r-f amplifier stage must provide a high order of "off-channel selectivity" rather than a high order of "adjacent channel selectivity" mentioned in Article 385. The latter can be obtained more easily and conveniently in the intermediate frequency amplifier, than in the preceding r-f circuits. The cross modulation effects which may occur in this first r-f amplifier tube due to strong local signals, have practically been eliminated by the development of the variable-mu type tube which may be used in this position, (see Art. 313).

Several forms of tuning circuits are suitable for the r-f amplifier. Since the action of the first tuned r-f stage in a superheterodyne receiver is exactly the same as that in a t-r-f receiver, the same forms of tuned circuits which have become popular for the first r-f stage in the latter types of sets are also used in modern superheterodynes.

Among these are the circuits shown in Fig. 280. A single tuned circuit arrangement is shown at (A). The secondary of the r-f transformer which couples this r-f amplifier tube to the first detector is also tuned. At (B) a band-pass pre-selector arrangement of the ordinary capacity-coupled type is shown. This type of circuit provides more selectivity than that at (A) and has been used extensively. At (C) is a very efficient arrangement in which the left hand or first tuned circuit is a rejector stage across the antenna and ground circuit. The action of this is to allow signal currents of frequencies above and below that of the wanted signal to flow without opposition through coil L, thus shunting them from the primary M. Between the antenna system and the r-f tube is another tuned circuit of the series resonance type. The combined selective effect of these two tuned circuits is higher than that of the

conventional selector stage of (B) and, shows in addition, a higher voltage transfer from tne antenna to the r-f tube, since this system does not show as much loss as the average dual-selector stage employed in most r-f circuits.

This arrangement gives a high order of both adjacent-channel and image-frequency selectivity and when used with a variable-mu type tube, results in freedom from cross-modulation. Coils suitable for the arrangements of (A) and (B) are shown in Fig. 281. At the left is that for the single tuned circuit, at the right is that for the band-pass circuit. In each case the primary winding is of the high inductance—high impedance type, lattice—wound in a narrow form. This inductance is so large that in



Courtesy General Mfg. Co.

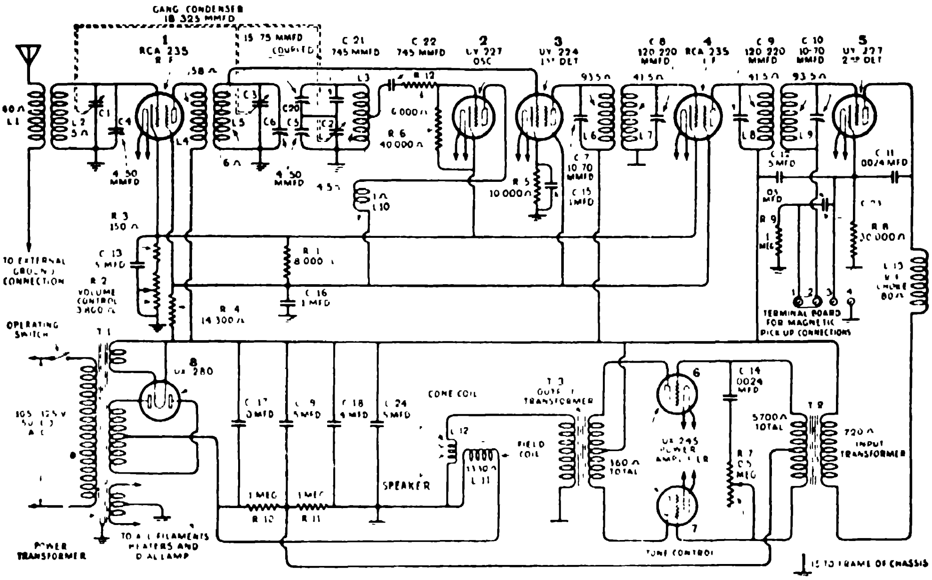
Fig. 281—Left Antenna coil suitable for use in the circuit arrangement shown at (A) of Fig. 280.
Right Antenna coil suitable for use in the arrangement shown at (B) of Fig 280
In each coil, the narrow primary at the left, is of the high impedance type, lattice-wound The secondary is the long winding

combination with the capacity of the antenna circuit it is in resonance to a frequency below that of any frequency to be received. At the lower broadcast frequencies where most receivers are insensitive, the use of a primary of this type results in somewhat greater gain than when a low-inductance primary is used. This was explained in Art. 371.

388. The oscillator: The function of the *local-oscillator* is mainly to generate a steady high frequency a-c voltage or current. Its frequency must be variable within the range necessary to produce beats of the fixed frequency for which the intermediate amplifier is designed, with every signal which it may be desired to receive. All forms of oscillators operate by feeding back energy from the plate circuit to the grid circuit. Since in a vacuum tube containing more than 2 electrodes, the available energy in the plate circuit is greater than that in the grid circuit, if part of this energy in the plate circuit is fed back to the grid circuit in sufficient amount and proper phase relationship of the instantaneous voltages, there will be constant re-amplification and feeding back of energy from the plate to the grid circuit. The frequency of the oscillations so produced will be determined by the inductance and capacitance of the tuned grid or plate circuit and their amplitude will depend on the shape of the family of E_g - I_p characteristic curves, the rate at which the power is dissipated in the entire circuit, and the amount of energy fed back to the grid circuit. The energy may be fed back through the plate-grid capacity of the tube as has already been explained, or it may be fed back by coupling the plate circuit to the grid circuit by the inductive action between coils connected in the grid and plate circuit (as in Fig. 282 and 283), or even by external capacity coupling with condensers. All forms of oscillators are not really suitable for use in superheterodyne receivers.

If the tuning circuit of the local-oscillator interacts with other tuning circuits in any way, there will be a change in local-oscillator frequency as these circuits are tuned. For this reason the circuit position of the oscillator is usually arranged by inductive coupling to an auxiliary winding in the cathode return, or the grid lead of the first detector circuit, so that detuning effects are negligible.

Many types of oscillator systems may be used in superheterodyne



Courtesy R C A. Victor Co.

Fig 282—Complete circuit diagram of an a-c operated superheterodyne receiver employing two 175 kc intermediate frequency amplifier stages, and a t-r-f stage ahead of the first detector

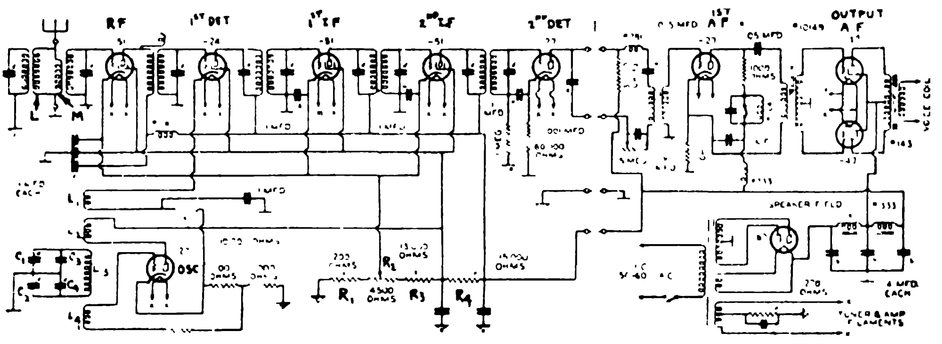
design, but the simple tuned-grid oscillator answers every requirement. The oscillator may be coupled to the mixer circuit in several ways. It may be coupled inductively by a coupling coil; by mutual induction; by means of a high resistance and small capacity in series; or by means of the screen-grid or cathode. Of these ways, mutual-induction is the simplest and the one most economical of space and material.

The oscillator should be so designed as to deliver considerable power to the frequency changer, and this voltage should be as constant over the frequency band as possible. With a little care, the voltage change over the frequency band can be made less than 3 to 1. The r-f voltage delivered to the frequency changer should be so adjusted, by varying the coupling to the oscillator, as to give maximum sensitivity without overload of the frequency changer at any frequency. The allowable voltage will depend upon the point at which the frequency changer is being worked.

The ideal local-oscillator should possess the following characteristics:

It should produce a constant frequency at any setting; should produce constant frequency free from objectionable harmonic frequencies; it should have constant power output over the tuning range; should radiate a minimum of energy into space to be picked up by other nearby radio receivers; and should produce minimum detuning action on the rest of the circuit through electrostatic and magnetic coupling. In some receivers, constant power-output of the oscillator over the full tuning range is not desired. In these, the output of the oscillator is purposely made greater for those frequencies at which the sensitivity of the receiver as a whole would be rather low. In this way, the sensitivity is made more uniform. Oscillator coils should be shielded to prevent radiation of energy to nearby receiving systems.

Two popular types of oscillator circuits for superheterodynes are shown in the superheterodyne receiver circuit diagrams in Figs. 282 and 283. In Fig. 282, the out-



Courtesy Silver Marshall Co., Inc.

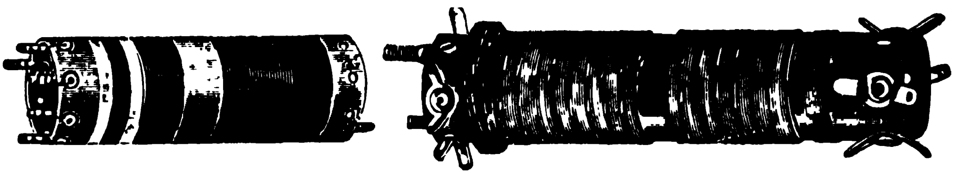
Fig 283—Complete circuit diagram of a typical a-c operated superheterodyne receiver employing a tuned rejector antenna circuit, and two 175 k c tuned intermediate amplifier stages Dual tone control is provided in the audio amplifier.

put of the oscillator is inductively coupled to the grid coil of the first detector. This is a tuned-grid circuit oscillator having a closely-coupled plate coil that gives sufficient feedback to provide stable operation. The peculiar grid circuit tuning arrangement shown is so designed that by means of a correct combination of capacity and inductance, a constant frequency difference (equal to 175 kc, the intermediate frequency) between the oscillator and the tuned r-f circuits is obtained.

In Fig. 283 the oscillator uses what is known as a "tank" tuning circuit which is substantially dissociated from the oscillator tube so far as frequency stability is concerned. Energy is fed back from plate coil L_2 to grid coil L_4 by magnetic coupling between L_2 and L_3 and between L_3 and L_4. The oscillator signal is fed to the grid circuit of the first detector tube by means of the coil L_1 connected in the cathode circuit. Since L_1 is between the cathode and the 10,000 ohm grid bias resistor of the first detector, the voltages induced in it by magnetic coupling with L_2 are impressed on the grid circuit.

Two forms of oscillator coils for superheterodyne receivers are shown in Fig. 284. The coil at the left has three windings, one for the grid tuning circuit, one for the tube plate feedback, and a small coupling coil for inducing the oscillator voltage into the grid circuit of the first detector. At the right is a single unit containing the coils L_4, L_5, L_3 and L_{10} from left to right in the order given, in the circuit diagram of Fig. 282. It is poss-

ible to operate the oscillator so that its frequency is always ***higher*** by a fixed amount (equal to the i-f), than the signal frequency, or operate it so its frequency is lower than that of the signal by this same amount, for in either case the frequency *difference* between the two will be the same. In practice, because of image-frequency interference considerations, the oscillator frequency is usually made *higher* than the signal frequency.



Courtesy General Mfg. Co.

Fig. 284—Left Oscillator coil with coupling, plate, and grid windings.
Right Oscillator coil with windings L4, L5, L3, and L10 for use in the type of circuit shown in Fig 282

389. Single control of the tuning circuits: The problem of achieving single-control of all the tunable circuits in a modern superheterodyne receiver is one which long defied the ingenuity of receiver designers. In the circuit of Fig. 282 for instance, C_1 and C_3 are the tuning condensers which must be varied to tune the circuits to exact resonance to the frequency of the incoming signal. These condensers may be made to track up easily enough if a gang condenser is used for tuning. However, condenser C_2 must tune the oscillator circuit to a frequency always exactly 175 kc higher than that to which the other two circuits are tuned, if the intermediate frequency is 175 kc. This problem has been solved in practice in two ways. One is to use a gang condenser in which the plates for C_1 and C_3 are similar but in which the plates of C_2 are shaped properly to give the proper tuning curve (so frequency is always 175 kc *higher* than the other two) under the circuit conditions for that section. These shapes have been worked out sufficiently close, and condensers designed especially for this purpose are available for use in practical single-control receivers.

The other solution is to use a gang condenser having exactly similar sections, but provide a "pad" circuit arrangement, which automatically balances up the inequalities in the tuning circuits.

The theoretical considerations involved in the design of these are too complex for presentation here, but it will suffice to say that a rule for the type of network shown in the circuits of Fig. 282 and 283 has been worked out experimentally. Referring to Fig. 282, this states that if tuning condensers C_1, C_2 and C_3 are alike, and C_{21} is made about twice the value of C_3 or C_2 at its maximum setting, for an oscillator inductance 22% less than L_5 (this value is not critical) the rate of change of the total

capacitance in the oscillator circuit will be such as to give a tuning curve which maintains the oscillator frequency a given fixed value above the frequency of the second detector grid circuit for any setting. The two small capacitances C_{20} and C_5 are simply small midget condensers, which are employed to align the circuits at the high and low wavelength ends, respectively, of the tuning range.

The trimmer condenser C_5, across the tuning section of the oscillator network, adjusts the minimum capacity of the system, and thus effects an alignment of the oscillator circuit at the low wavelength end of the range. The other fixed condenser trimmer C_{20}, serves to effect a similar alignment at the high wavelength end of the spectrum. Tracking throughout the mid-range will be perfect enough to avoid any necessity for the use of a manually-operated trimmer while tuning. The same form of tuner circuit is employed in the oscillator circuit of Fig. 283. If signals of any station in the broadcast range (550 to 1,500 kc) are to be received, and the intermediate frequency is say, 175 kc, the range of the oscillator must be from 550+175 or 725 kc to 1,500+175=1675 kc.

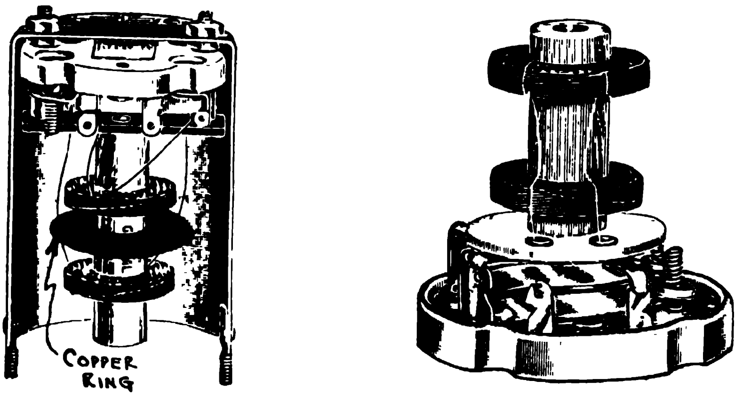
390. Choice of the intermediate frequency: The selection of the value of the intermediate frequency employed is very important. The choice of the intermediate frequency has, in the past, often seemed a matter of the set-designer's whim, but actually, it is definitely settlea by the conditions of the actual problems involved. Let us see what they are.

For high amplification and good selectivity, the lower the i-f, the better, whereas for freedom from image-frequency interference, the higher the i-f the better. As the image-frequency problem is perhaps the most serious one, a high i-f might seem to be best, but another factor enters, limiting the upper limit of i-f which may be employed in practice. Any detector generates some harmonics of the r-f signal carrier applied to it, and in the case of a power detector handling high signal voltages, harmonics, up to the third, represent quite a fair percentage of the fundamental. It has been found that if the third harmonic of the i-f falls in the broadcast band, leakage in the set from second detector output back to first detector can cause serious interference problems, so that the i-f should be low enugh to keep its third harmonic below the broadcast band. The third harmonic of 175 kc, for example is 525 kc, just safely below the broadcast band, and therefore 175 kc has been chosen as the intermediate frequency in many modern receivers. The reason why 170 kc is not chosen, is that the choice of an i-f that is a multiple of 5 kc rather than 10 is desirable, since broadcasting station frequencies in the United States are separated by 10 kc, and two stations themselves separated by 170 kc or 180 kc will cause less trouble to a sharp 175 kc i-f amplifiier than they would to a 170 kc amplifier. This has been discussed in Article 386.

391. The intermediate amplifier: The function of the intermediate-frequency amplifier is to amplify a band of frequencies not more than 10 kilocycles wide (with the present broadcast and audio range of 5,000 cycles), that is 5 kc on either side of the value of the intermediate frequency it is designed for. Screen-grid tubes are commonly employed in i-f amplifiers on account of their high amplification factor. It is possible to obtain an actual amplification of 80 or so per stage in a well designed i-f amplifier. The tubes could be coupled together by resistance, transformer, or impedance coupling, but since the i-f amplifier is a fixed-frequency amplifier, it presents a splendid opportunity for the use of band-pass tuners designed to produce actual results close to the theoretical ideal. The simple form with a tuned primary and tuned secondary with

magnetic coupling between the coils is commonly employed on account of its cheapness and simplicity. Fig. 282 shows the arrangement of two such stages. In Fig. 283, three are used.

The interstage transformers are designed with a large ratio of L to C, and small adjustable compression type mica condensers having a range of approximately 100 to 200 mmf. are used to tune each winding to the frequency required. Many of the smaller midget receiver designs contain only a single intermediate stage, and for this single stage amplifier the transformer should be designed so that the stage will have a gain approximately seven times as great as when two stages are used. This can be done by winding the coils with litzendraht wire, keeping the ratio of L to C higher



Courtesy General Mfg. Co.

Fig 285—Left Intermediate-frequency transformer for coupling first detector to first i-f amplifier tube The coupling between the primary and secondary is made loose by means of the copper ring between.
Right Same type of i-f coil for the other i-f stages. The tuning condensers are in the base

than the ratio for the two stage transformers. The mutual inductance between the windings is chosen so that the resonance curve will approximate a flat top, with band-pass characteristics.

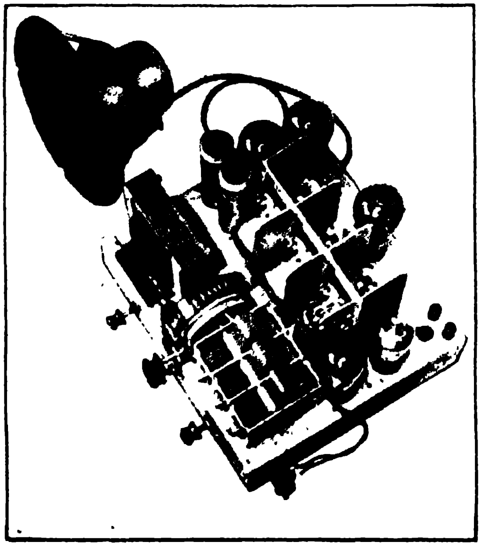
The proper value of mutual inductance cannot be expressed as a certain distance between the primary and secondary coils, because this distance will vary with different amplifier designs. To secure the proper degree of selectivity it is necessary, as a rule, to use less coupling between the tuned circuits of the first stage than is used in the succeeding stages. In cases where the physical dimensions of the shields have prevented sufficient separation of the coils to reduce the coupling to the proper value, small copper ring shields have been used between the coils with good success. These copper rings may then be bent until the coupling is just the proper value. This ring shield is usually employed only in the first stage transformer. A unit of this type is shown at the left of Fig. 285, with its enclosing shield cut away to show the interior. One of the intermediate coils without the ring is shown at the right. The tuning condensers for each coil unit are mounted below the respective coils.

As all the circuits of the intermediate amplifier are tuned, it is vital in order to preserve the proper selectivity and amplification, that the adjustable tuning capacities have good electrical properties. They must also be mechanically correct so that they will permanently hold their adjustment without change in capacity value.

A commonly used mounting for the small universally wound coils, which are employed for the tuned intermediate circuits, is wooden doweling. There is no objection to this material provided that it is impregnated with wax, so that the wax penetrates entirely through the wood. The intermediate transformer assemblies should be shielded.

It is quite possible to properly design a superheterodyne of "midget" proportions and still retain the full amount of amplification as used in the

larger receivers of this type. It can be made to perform as well as the larger receivers in everything but reproduction, and even here it would not fail if it had an equivalent amount of baffling for the reproducer. The complete chassis of a midget superheterodyne receiver of this type, complete with its electro-dynamic type loud speaker is shown in Fig. 286. The sensitivity of this particular receiver is 6 to 10 microvolts per meter. The three gang condenser which tunes the dual antenna circuit selector



Courtesy Silver Marshall Co., Inc.

Fig. 286—The chassis and loud speaker of a typical midget type superheterodyne receiver. The chassis measures only 12 inches wide. The sensitivity is 6 to 10 microvolts per meter.

and the oscillator circuit is seen at the lower left of the chassis. The chassis of this set is only 12 inches wide.

392. The second detector: The second detector employed should be of the power type. Only a single audio stage is used in most supers because the gain of the receiver is so high that a second audio stage would be of no advantage and would tend to increase the hum in a-c operated receivers. The use of but one audio stage requires less "B" power supply filtration, but more i-f gain, which however, is easier to obtain in a super than is additional audio gain. The circuit of Fig. 282 shows the connections for a '27 type power detector feeding into a single audio stage. In Fig. 283, the second detector feeds into two audio stages, used on account of the special audio tone-control employed.

393. Arithmetical selectivity: Another advantage of the superheterodyne receiver is that due to the so-called *arithmetical selectivity* which is obtained. This can best be illustrated by considering the problem

of selecting a wanted station at, say, 1,000 kc and yet completely eliminating an unwanted station at 1,010 kc.

The frequency separation is seen to be 10 kc, or 1 per cent, and such separation presents problems which no t-r-f receiver (even one employing five or six tuned circuits), can completely satisfactorily meet. In the case of the superheterodyne however, where the intermediate amplification frequency may, for this purpose, be considered as a frequency of 175 kc, it is apparent that when the wanted and unwanted signals are both heterodyned, they will appear 10 kc apart at the intermediate-frequency amplifier. That is, the wanted stations will appear at 175 kc and the unwanted station will still be 10 kc away. The percentage difference in this case is seen to be about 5.7 per cent and it is apparent therefore, that the relative selectivity problem is approximately six times simpler for the super with 175 kc i-f amplifier than for the t-r-f set which must perform discrimination between original signals of 1,000 and 1,010 kc.

394. "Repeat" points: With many of the old 2-dial control superheterodynes, it is possible to tune a single station in at two separate settings of the oscillator dial, or tune in two separate stations with a given setting of the oscillator dial. This is due to the fact that the oscillator tuning control and the antenna circuit tuning control are separate and that insufficient selectivity is provided ahead of the first detector.

The incoming signal can be converted to the beat frequency when the oscillator frequency is the proper amount above its frequency (1 setting), and also when the oscillator frequency is the proper amount below its frequency (the other setting). To make this clear, let us suppose that the intermediate or "beat" frequency is to be 100 kc. If a signal of 550 kc is tuned in, the frequency of the oscillator can either be adjusted to 450 kc or 650 kc to provide this beat frequency of 100 kc. Also if the oscillator frequency were set at say 650 kc, and there were two stations operating at 550 kc and 750 kc equally powerful at the input to the receiver, both would provide the required 100 kc intermediate-frequency and both would be heard together. In modern single-control receivers, this is eliminated by providing adequate selectivity ahead of the first detector, using a moderately high i-f, and ganging the condensers together so the oscillator frequency is always an equal frequency above that of the antenna tuning circuits.

395. The "Autodyne": In the autodyne system, one tube is eliminated by combining the functions of the oscillator and the first detector. The input circuit from the antenna is coupled to the oscillator, which also acts as the detector. This is tuned so its frequency differs from the incoming frequency by the exact number of kc to which the i-f amplifier is tuned. A super of this type is called an *autodyne* because the signal is automatically heterodyned in the local oscillator or first detector, instead of requiring the additional mixing circuit and tube. Some loss in signal strength is experienced in autodynes, because the first detector is actually detuned from the incoming signal.

396. Frequency changers: The principle of the superheterodyne can be applied to any existing t-r-f receiver by adding an oscillator and a mixing tube. In a system of this kind, all of the tuning circuits of the r-f amplifier are set at some fixed frequency to give maximum amplification within the broadcast band. The tuned r-f amplifier is therefore used as the "intermediate amplifier" of the super system. The oscillator output produces beats with the incoming signals so that this intermediate frequency is generated and amplified. The signals are finally detected in normal manner by the detector in the t-r-f receiver. The oscillator must of course be designed to produce the proper range of frequencies, depending on what the intermediate frequency is to be. Superheterodyne type short wave converters are commonly used for receiving short wave programs. The oscillator produces beats at the lower frequencies to which the t-r-f amplifier of the receiver it is used with is tuned. These "frequency changers" or so-called *short wave converters* are discussed in detail in Art. 565.

397. Adjusting the circuits of a superheterodyne: In a superheterodyne receiver, it is essential that the tuning circuits controlled by the gang tuning condenser be kept accurately aligned. Also, the tuned circuits formed by the primary and secondary windings of the intermediate transformers must be adjusted accurately so as to pass a band of frequencies 5 kc above and below the i-f. The methods and apparatus used for adjusting these circuits will be considered in Art. 639.

REVIEW QUESTIONS

1. Show by means of a block diagram, the various parts of a superheterodyne receiver, and explain briefly the various changes which the signal undergoes as it proceeds through the set.
2. What is the essential difference between a t-r-f receiver and a superheterodyne?
3. What is the main advantage of amplifying at an "intermediate frequency" lower than the frequency of the incoming signal?
4. State three advantages of the superheterodyne form of receiver over the ordinary t-r-f receiver for broadcast band reception.
5. Explain in detail the phenomenon of "beat frequencies" taking place when a voltage having a frequency of 1,000 kc and one having a frequency of 600 kc are made to act together in the same circuit. What is the frequency of the beats produced? What is the frequency of the resulting voltage?
6. A superheterodyne receiver with a 175 kc intermediate amplifier is to be designed for reception of signals over a frequency range of 500 to 3,000 kc. What must be the frequency range of the oscillator in this receiver?
7. Give one example of how image frequencies might be received by a superheterodyne. By what practical arrangement could they be eliminated?

8. What is the difference between adjacent-channel selectivity and off-channel selectivity? Which is most important in (a) the r-f amplifier stage of a superheterodyne; (b) in the i-f amplifier?
9. What factors influence the selection of the i-f for a broadcast superheterodyne receiver?
10. Why is it necessary to "demodulate" the combined output of the antenna and local oscillator, in order to obtain the beat frequency?
11. What form of coupling is generally employed between the i-f stages of a broadcast superheterodyne? What is the advantage of this form of coupling here?
12. Explain the fundamental principle of the operation of a vacuum tube as an oscillator.
13. What is the function of the oscillator? How is the output of the oscillator made to combine with the input signal?
14. Why must the frequency of the oscillator be varied for each different station received in a superheterodyne receiver? How is this accomplished?
15. What is the advantage of making the oscillator frequency always higher than the signal frequency?
16. What is the advantage of using a high-inductance primary loosely coupled to the secondary coil in an antenna coupling coil.
17. Why is a special "pad" circuit arrangement, or a condenser section with specially shaped plates, required for tuning the oscillator circuit in a single control superheterodyne?
18. Explain in detail some of the factors which govern the choice of a suitable i-f for broadcast band superheterodynes. What i-f is used in most supers now? What advantages does this frequency have over others?
19. What is the purpose of the "second detector?"
20. Explain what is meant by the "arithmetical selectivity" obtained by the beat action in a superheterodyne.
21. How may an ordinary t-r-f receiver be converted into a superheterodyne, using the tuned stages of the t-r-f set as the intermediate amplifier? What additional parts are necessary?

Chapter 23

DESIGN OF R. F. AMPLIFIERS AND TUNING COILS

TUNING CIRCUITS — FORMS OF INTERSTAGE COUPLING COILS — CALCULATING THE INDUCTANCE OR CAPACITANCE REQUIRED — DESIGNING THE WINDING BY USE OF FORMULAS — COIL DESIGN BY MEANS OF CHARTS — DESIGN OF THE PRIMARY WINDING — EFFECT OF VARYING THE COUPLING — CONSTANT R. F. COUPLING — LOSSES IN TUNED COILS — DISTRIBUTED CAPACITY — COIL SHAPES AND TYPES OF WINDINGS — INTERSTAGE COIL COUPLING — R. F. COIL PROPORTIONS — PLACEMENT OF R. F. COILS — SHIELDING IN R. F. AMPLIFIERS — EFFECT OF SHIELDING ON TUNING COIL — GENERAL SHIELDING CONSIDERATIONS — REVIEW QUESTIONS.

398. Tuning circuits: We have seen that both the t-r-f and the superheterodyne forms of tuners used in radio receivers depend for their operation on electrical resonance produced in tuned circuits consisting usually of inductances and condensers of proper values depending on the frequency range to be received. If the circuit is to be tuned at will to any frequency within a certain specified frequency band, the coil is usually of fixed inductance and the tuning condenser is of the variable type. If the combination is always to be in resonance at some one fixed frequency, both the inductance and the condenser are made fixed, or the latter is semi-adjustable, as in the case of the i-f tuning coils in the superheterodyne. Thus far, we have referred to the coupling coils or transformers used for this purpose, in a rather abstract way, no attempt being made to study their design in detail. This will be considered now. Several forms of coils in superheterodynes were shown in Chapter 22.

399. Forms of interstage coupling coils: The tendency in modern t-r-f receivers is toward the use of the air-core type of r-f transformers in which the primary and secondary windings are on thin tubes of insulating material such as Bakelite or Formica. The use of iron cores is of course objectionable on account of the excessive eddy current and hysteresis losses at these high frequencies unless special design precautions are taken. Some interesting r-f transformers have been produced with special chemically treated compressed iron dust cores, in which each particle of iron is insulated from the next by a thin insulating film of oxide, etc., but they have not attained much commercial success. The windings consist of either cotton, silk or enamel covered copper magnet wire, the latter being used extensively on account of its lack of moisture absorption and better mechanical characteristics for quantity-production

machine winding. The secondary winding is usually tuned by a variable condenser to produce resonance. We have already studied in detail, in Articles 172 to 178 and elsewhere, the actions which take place in the tuned circuit, so we will not repeat them again here. Suffice it to say, that the inductance and capacity required to form a resonant circuit at any frequency or wavelength can be calculated by formulas or may be found quickly by charts arranged especially for this purpose.

The usual procedure in designing tuning coils, is to design the tuned winding or inductance first, since this depends in any case, on the size of the tuning condensers employed, and the frequency, or frequency range, over which resonance is to be obtained. The sizes and design of tuning condensers employed for use in t-r-f circuits has been fairly well standardized in the U. S., as explained in Articles 150 to 154, variable tuning condensers having a maximum capacitance in the neighborhood of .00035 mf. being used most in broadcast-band tuners.

400. Calculating the inductance or capacitance required: Any inductance in combination with a given capacitance (as in Fig. 223 for instance), will be in resonance or in "tune" at a certain definite frequency or wavelength which may be calculated from the equations already discussed in Articles 116, 173, 176 and 177. These will be summarized here for convenience: First, the resonance frequency in cycles per second is found from the equation:

$$f = \frac{159{,}000}{\sqrt{L\ (\text{Microhenries}) \times C\ (\text{Microfarads})}} \qquad (1)$$

$$\text{from which } L = \frac{2.528 \times 10^{10}}{f^2\, C} \qquad (2)$$

$$\text{or, } C = \frac{2.528 \times 10^{10}}{f^2\, L} \qquad (3)$$

The wavelength in meters, at which resonance takes place is found from:

$$\text{Wavelength} = 1885 \times \sqrt{L\ (\text{Microhenries}) \times C\ (\text{Microfarads})} \qquad (4)$$

$$\text{from which } L = \frac{\text{Wavelength}^2}{3.55 \times 10^6 \times C} \qquad (5)$$

$$\text{or, } C = \frac{\text{Wavelength}^2}{3.55 \times 10^6 \times L} \qquad (6)$$

The self-inductance of an *air-core solenoid* coil in *microhenries*, is approximately equal to:

$$L=0.0251\ d^2\ n^2\ l\ K \quad \text{.......................} \quad (7)$$

Where n=the No. of turns per inch (see magnet wire table in Fig. 288 for particular size and kind of wire being used).
d=mean diameter of the solenoid in inches.
l=the length of the solenoid when wound (inches).
K is the "form factor" (Nagoaka's correction factor), which depends for its value on the ratio obtained by dividing the diameter by the length of the winding. Values of K for various diameter-length ratios are given in the following table.

VALUES OF "K" FOR USE IN FORMULA (7), ABOVE

Diam./length	K	Diam./length	K	Diam./length	K	Diam./length	K	Diam./length	K
0.00	1.0000	1.20	.6475	2.80	.4452	5.40	.3050	16.00	.1457
.10	.9588	1.30	.6290	3.00	.4292	5.80	.2916	18.00	.1336
.20	.9201	1.40	.6115	3.20	.4145	6.20	.2795	20.00	.1236
.30	.8838	1.50	.5950	3.40	.4008	6.60	.2685	21.00	.1078
.40	.8499	1.60	.5795	3.60	.3882	7.00	.2584	28.00	.0959
.50	.8181	1.70	.5649	3.80	.3764	7.40	.2491	35.00	.0808
.60	.7885	1.80	.5511	4.00	.3654	7.80	.2406	45.00	.0664
.70	.7609	1.90	.5379	4.20	.3551	8.50	.2272	60.00	.0528
.80	.7351	2.00	.5255	4.40	.3455	9.50	.2106	80.00	.0419
.90	.7110	2.20	.5025	4.60	.3364	10.00	.2033	00.00	.0350
1.00	.6884	2.40	.4816	4.80	.3279	12.00	.1790	......	....
1.10	.6673	2.60	.4626	5.00	.3198	14.00	.1605	......	....

NOTE: This formula assumes the coil to be wound with an infinitely thin conducting tape, the edges of which touch, though electrically insulated. The correction for the commercially available conductors commonly used is relatively small and may be neglected so far as practical results are concerned.

Calculations involving the use of equation (1) may be simplified by the use of the table of L C values which will be found in Appendix I. By means of equations (2), (3), (5) or (6) the required value of either the inductance or the capacity may be calculated, if either the wavelength or the frequency are known. These are all derived from the same formula, but are given here in order to make the calculations convenient. It should be remembered that in a practical tuned circuit used in a radio receiver, the capacity of the tuning condenser is not the only capacity that tends to tune the inductance. As shown at (B) of Fig. 266, the mutual coupling capacity to the primary (if one is used), the distributed capacitances of the coil, and wiring, input grid-cathode capacity of the tube, etc. all act to tune the coil. Therefore if accurate calculations are desired, the sum of these must be considered as the effective tuning capacitance. For rough determinations however, only the tuning condenser capacitance is considered and one or two turns of wire less are used on the coil to allow for the other stray capacitances.

Problem: What must be the inductance of the secondary winding of an r-f transformer if it is to tune to a wavelength of 600 meters (500 kc) when the variable tuning condenser of .00035 mf. is set at maximum capacitance?

Solution: from equation (5) we find,

$$L=\frac{\text{Wavelength}^2}{3.55\times10^6\times C}=\frac{600\times600}{3.55\times10^6\times.00035}=300 \text{ Microhenries (approx.)}$$

401. Designing the winding by use of formulas: After the value of inductance which is required is determined, the exact winding data for the coil must be found. This is really the most difficult part of the problem, for it depends on many factors. For instance, in the above problem, we found that a coil of 300 microhenries is to be used for the particular conditions mentioned. As we shall see later, there are various types of windings such as solenoid, honeycomb, torroid, etc., which could be employed. We will assume for simplicity that a simple solenoid winding is to be used, since this is the most efficient and widely used form employed in the tuned circuits of short wave and broadcast band, t-r-f receivers. The next thing to be determined, is the diameter of the coil. Here again we have a wide choice, but since modern receiver design requires small, compact coils, with very limited external magnetic fields, we will assume that our coil is to be wound say, one inch in diameter. Coils of 7/8, 1, or 1 1/4 inches in diameter are used extensively since they are compact, and may be shielded by metal shield cans of small size. Next, we have a choice of size of wire and kind of insulation to be employed. Enamel covered copper wire is used extensively, due to its many advantages which will be discussed later. Sizes from No. 22 B and S to No. 32 B and S gauge are being employed, the smaller sizes being used most, in order to keep the length of the coil winding short. Let us now see how the winding data is determined if the coil diameter and size to be used, are known:

From formula (7) we have: $L = 0.0251\, d^2 n^2 l K$. Since we must find l first and then find the number of turns for this length of winding from the magnet wire table, we can arrange this formula in the form,

$$l = \frac{L}{.0251\, d^2 n^2 K}$$

Now it is evident that the known factors are L and d. If the wire size is known, n may be also found from a magnet wire table such as that of Fig. 288. We do not know the value of K because this varies as the length of the winding is varied. Therefore we must assume an approximate value for the total number of turns and proceed with the calculation on that basis. If we have had some experience in designing windings of this type, we will probably be able to assume this value for the number of turns, close to the actual value. Then the value of K corresponding the length of the coil with these turns is found from the table. The computations must be carried out on this basis. The coil diameter must then be divided by the length of the winding obtained, and the value of K for this ratio must be checked back against the value assumed. If they differ greatly, a new value for the length of the winding must be assumed, and the calculation made over again. This procedure must be repeated until the correct values are found.

402. Coil design by means of charts: It is evident that the use of the formulas for the design of a solenoid tuning coil is not very convenient because of the involved computations necessary. In order to simplify this work and obtain results accurate enough for ordinary coil design work, special charts have been devised, which enable one to design a solenoid coil in a few minutes simply by the use of a straight-edge, pencil and paper. The charts for this purpose have been arranged together with complete instructions for their use in Fig. 287. Chart No. 1 at the left may be employed to find the inductance or capacitance if the wavelength of resonance is known. Chart No. 2 is for finding the coil design data. A

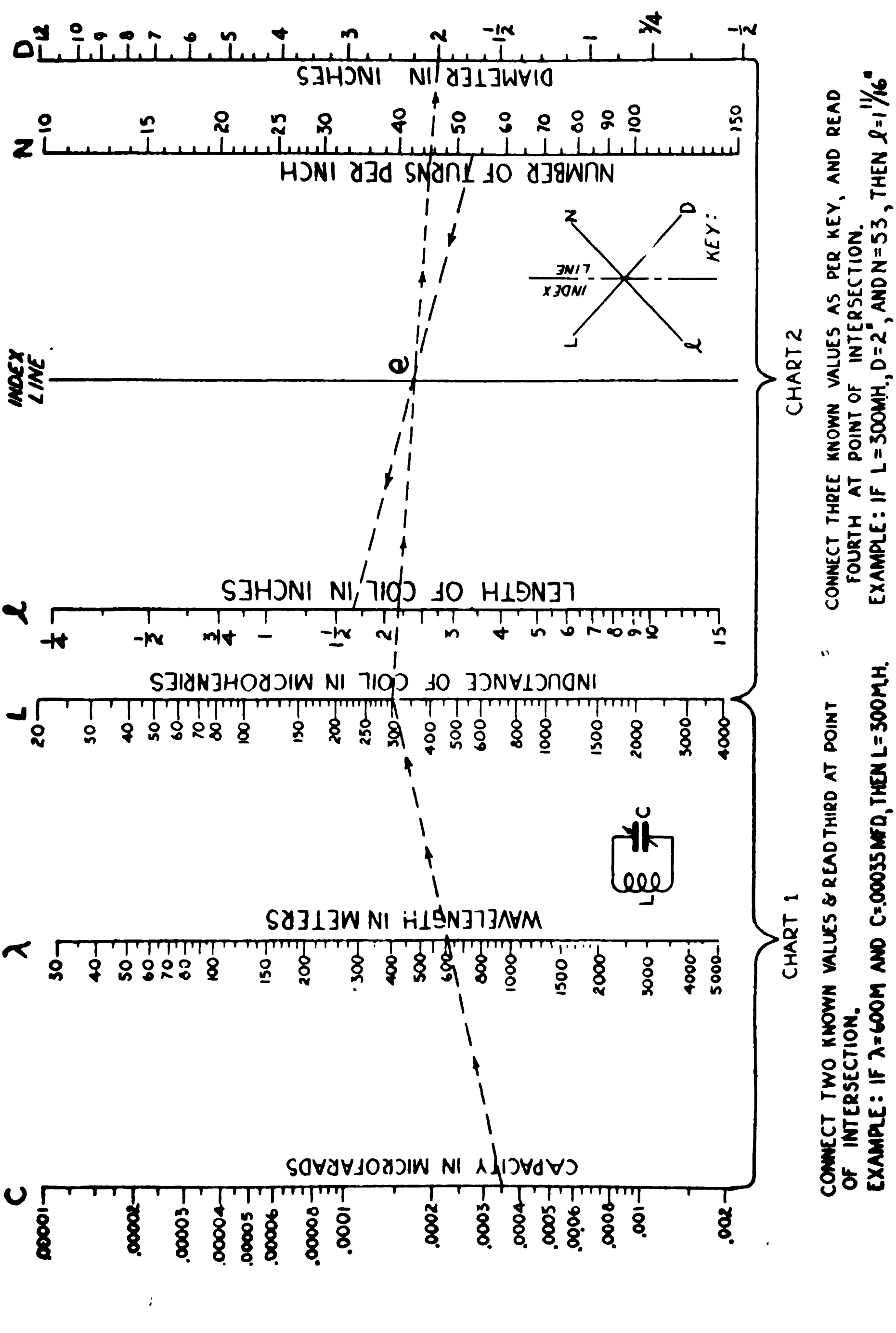


Fig. 287—Charts for rapid design of solenoid type tuning coils. Their use is explained in the text.

SIZE B.&S.	DIAMETER IN MILS.	AREA IN CIR. MILS.	FEET PER OHM	FEET PER POUND					OHMS PER 1000 FT AT 68° F.	TURNS PER INCH						APPROX. COST PER LB. (CENTS) ADD 5% FOR GREEN SILK				
				BARE	SINGLE SILK S.S.C.	DOUBLE SILK D.S.C.	SINGLE COTTON S.C.C.	DOUBLE COTTON D.C.C.		BARE	ENAMEL	SINGLE SILK S.S.C.	DOUBLE SILK D.S.C.	SINGLE COTTON S.C.C.	DOUBLE COTTON D.C.C.	ENAMEL	SINGLE SILK (WHITE) ADD 5% FOR GREEN SILK	DOUBLE SILK (WHITE)	SINGLE COTTON	DOUBLE COTTON
14	64	4100	396	80.4					2.58	15.6	14			14	13	21			23	24
15	57	3260	321	101.4					5.25	17.5	16			15	14	22			24	26
16	51	2580	249	127.9					4.09	19.6	18			17	16	22	38	50	25	28
17	45	2050	197	161.3					5.16	22.	21			20	18	23	39	52	27	29
18	40	1620	156.5	203.4					6.51	25	23			22	20	23	39	55	28	31
19	36	1290	124	256.5					8.21	27.8	27			25	22	24	42	62	30	33
20	32	1020	98.4	323.4	319	312	311	298	10.4	31	29	27	25	27	25	25	47	67	31	36
21	28.5	810	78.1	407.8	398	389	389	370	13.1	35	32	30	27	30	27	27	51	73	34	39
22	25.3	642	61.91	514	504	493	491	461	16.5	39	36	34	30.5	34	30	26	52	83	34	42
23	22.6	509	49.09	648	645	631	624	584	20.8	44	40	38	34	37	32	27	54	89	35	47
24	20.1	404	38.92	818	795	779	778	745	26.2	50	45	43	38	41	35	28	61	98	38	51
25	17.9	320	30.86	1031	1004	966	958	903	33	56	50	47	41	45	38	29	67	109	42	58
26	15.9	254	24.47	1300	1240	1202	1188	1118	41.6	63	57	52	45	50	41	31	75	121	45	62
27	14.2	202	19.41	1639	1615	1542	1533	1422	52.5	70	64	58	50	55	45	33	81	139	50	71
28	12.6	160	15.39	2067	2023	1917	1903	1759	66.2	79	71	64	53	60	48	35	94	149	55	85
29	11.3	127	12.21	2607	2625	2485	2461	2207	83.4	88	81	71	58	65	51	37	105	167	61	93
30	10	101	9.68	3287	3325	2909	2893	2534	105	100	88	80	66	71	55	40	115	200	68	109
31	8.9	79.7	7.86	4145	3820	3683	3483	2768	133	112	104	87	71	76	58	43	133	219	83	124
32	8	63.2	6.09	5227	4876	4654	4414	3737	167	125	120	99	76	84	62	43	149	259	94	148
33	7.1	50.1	4.83	6591	6243	5609	5688	4697	211	141	130	105	83	90	66	45	174	304	107	168
34	6.3	39.8	3.83	8311	7757	7111	6400	6168	266	159	140	110	88	97	69	47	211	345	127	205
35	5.6	31.5	3.04	10480	9660	8534	8593	6737	335	179	160	130	104	104	73	51	242	405	152	236
36	5	25	2.41	13210	11907	10040	9846	7877	423	200	190	140	110	117	82	58	294	488	176	268
37	4.5	19.8	1.91	16660	13474	10670	11636	9309	533	222	205	150	115	123	85	68	344	590	208	292
38	4	15.7	1.51	21010	16516	14220	13848	10660	673	250	225	160	120	130	88	83	464	746	243	353
39	3.5	12.5	1.2	26530	22260	16520	18286	11910	848	285	255	180	130	142	90	102	548	891	289	399
40	3.1	9.9	.95	33410	26950	21330	24381	14220	1070	321	280	200	140	151	92	139	693	1149	346	452

Fig. 288—Table of useful information on copper wire with various kinds of insulation, such as is employed for tuning coils, inductors, transformer windings, etc. This is useful in conjunction with the charts of Fig 287

convenient table giving the turns per inch, feet per pound, etc. of the many sizes and types of wire is given in Fig. 288. The use of these is illustrated by the following problem:

Problem: What must be the inductance of the secondary winding of an r-f transformer if it is to tune to 600 meters when the variable tuning condenser of .00035 mf. is set at maximum capacitance? The coil is to be wound with No. 28 double silk covered (d. s. c.) wire, on a two-inch diameter form. Find the number of turns required for the winding and the length of the winding.

Solution: First use chart No. 1 in Fig. 287. Lay a straight edge on the chart so it connects the points representing the two known values, i.e., wavelength=600 meters and tuning capacitance=.00035 mfd. The required inductance is read at the intersection of the straight edge with the inductance scale (L). It is 300 microhenries (the dotted lines on the chart have been drawn to show the condition for this problem).

The dimensions of the coil can be found easily from the chart No. 2 at the right and the wire table of Fig. 288. A line is drawn from the 300 point on the common L scale, to "2" on the coil diameter scale (D), intersecting the index line at point "e". Referring to the magnet wire table of Fig. 288, we find that No. 28 double silk covered wire winds to 53 turns per inch. Another line is now drawn from this value on the "turns per inch" scale (N), through intersection point "e". It is found to intersect the coil-length scale (l) at about 1.7 inches. This means that the coil should be wound to a total length of 1.7 inches. Since this wire winds to 53 turns per inch, there will be 53×1.7 or 90 turns of wire on the coil. Ans.

The charts can be also operated in the reverse direction, always making sure that the correct pairs of scales are connected together, as shown by the "Key" at the lower right of the charts. Thus, if a coil has a certain number of turns of wire of a certain kind and size on a certain size of form, its inductance may be found.

In order to find the exact minimum wavelength (or highest frequency) to which the variably tuned circuit will tune, it is necessary to know the following factors: the minimum capacitance of the condenser; the distributed capacitance of the coil and wiring; the grid-cathode capacitance of the tube it works into; and the capacitance between the coil and metal shielding (if any is used). These capacitances all act to tune the coil. Let us suppose that in the above problem the total of all these capacitances at the minimum setting of the tuning condenser, is C=.00003 mf. Using this value for C, and 300 microhenries for L, we find from the charts, that the minimum wavelength to which the circuit will tune, is 180 meters (1,666 kc). This example shows how simple the design of tuning coils becomes, with the aid of the charts and wire table. They can be used in many ways, for finding any constant of a tuned circuit, when the other constants necessary are known.

It must be remembered that the values obtained by this method of coil design apply only to a single coil of wire isolated in space and connected to a tuning condenser. The moment another coil is brought into its vicinity, the conditions change since the magnetic fields interact and the inductance decreases. For instance, if this coil is to be used with an untuned primary coupled to it, it will be necessary to use one or two more turns on it than the number indicated by the charts. This also holds

true when a tickler coil is used with it. If the coupling between the various coils is loose however, there will not be much change in the inductance of the secondary, so no correction need ordinarily be made. The same design procedure applies to the coupling devices used in impedance or tuned-plate r-f amplifiers.

403. Design of the primary winding: The design of an untuned primary winding for an r-f transformer presents several difficulties, and in most cases the final design represents a compromise between several factors. Since the function of the primary coil is to transfer energy to the secondary through the medium of its magnetic field, it would seem that best results would be obtained by a large number of primary turns so closely coupled to the secondary coil that all of its lines of force link with the secondary. This condition would best be met by winding the primary on a form and placing it inside of the secondary either as a concentrated winding at the center or a distributed winding equal to the length of the coil. However, a consideration of the principle of pure transformer action as studied in Article 111, shows that greatest voltage step-up in the transformer is obtained by making the ratio of the secondary turns to the primary turns as great as possible. Since the secondary turns are determined and fixed by the size of the tuning condenser used and the lowest frequency to which the circuit is to tune, this would mean using only a few turns for the primary winding in order to get a large step-up ratio. However, the conditions in r-f transformers are quite different, for since no iron core is employed, not all of the lines of force of the primary link with the secondary, that is, there is a large *magnetic leakage*. Therefore, if we used only a few turns on the primary, so few lines of force would link with the secondary, that very little voltage would be induced in the secondary at all. The ratio of the number of secondary to primary turns is no indication of the voltage step-up under such conditions—in fact, in an air-core r-f transformer having say 60 secondary turns and 15 primary turns (4 to 1 turns ratio), an actual voltage step-up of only 1.2 or 1.4 might be actually obtained, due to the loose coupling necessary for selectivity. Also a consideration of the theory of the vacuum tube as an amplifier, as presented in Article 336, shows that the amplification or gain produced by the tube is equal to $G=\mu\times\frac{R_o}{R_o+R_p}$ where R_p is the plate resistance of the tube and R_o is the plate load resistance. Therefore in order to secure a large proportion of the possible amplification factor of the tube, it is desirable and necessary that the load resistance (which is the primary of the coupling transformer in this case) be as large as possible. Thus, if the load resistance is 3 times the plate resistance of the tube, 75 per cent of the mu of the tube is obtained, etc. A glance at the table of Fig. 214 will show that the plate resistance of most amplifier tubes is high, especially that of screen-grid tubes which it is desirable to use, so that the primary of the coupling transformer should

have a high impedance (large number of turns) in order to secure high gain from the tube. It is evident that the final design is always a compromise between the various factors encountered. In practice the tendency has been to use primaries of 40 or more turns of wire when screen grid r-f tubes are used, in order to obtain sufficiently high plate circuit load for high amplification.

The coupling between the primary and secondary depends on the degree of selectivity required, the number of tuned stages used, etc. The

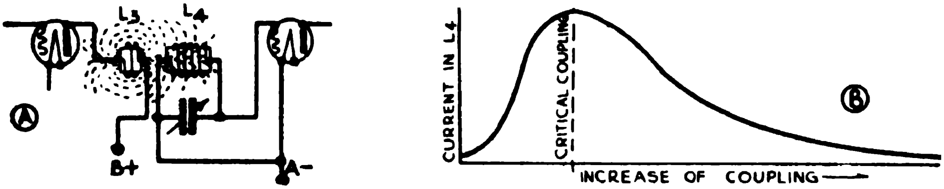


Fig. 289—Effect, on the induced secondary voltage and current, of variation of the magnetic coupling between the primary and secondary windings of an interstage r-f coupling transformer.

value of coupling used, and the exact mechanical arrangement and relation of the primary to the secondary coil is always determined finally by actual trial and experiment for any given receiver design. Two designs of r-f transformers actually used in high-gain screen-grid r-f amplifiers are shown at (B) of Fig. 290. The one at the right, with the prongs, has the primary consisting of about 40 turns of silk covered nichrome wire wound directly over the grid return end of the secondary with a strip of celluloid insulation between them. The secondary is underneath. This arrangement provides rather tight coupling and the selectivity may not be great enough for some reception conditions. The coil design at the left is more desirable in many cases. It has a high inductance primary of many turns of fine wire, wound in a slotted form placed inside of the grid return end of the secondary, but about ¼ inch away from it. This provides the high plate load impedance necessary for high amplification with the screen-grid r-f amplifier tube used, at the same time providing loose enough magnetic coupling for good selectivity. A small capacity-coupling coil C, one end of which is connected to the primary and the other end of which is open, provides a small capacity-coupling for making the transfer of energy more uniform over the broadcast frequencies. In the case of the band-pass coils such as are used in the intermediate amplifiers of superheterodynes, since the primaries and secondaries are usually similar, the primary coil design is automatically fixed by the frequency of the i-f amplifier and the small tuning condenser employed. The amount of magnetic coupling between them is determined by the width of the frequency band to be passed.

404. Effect of varying the coupling: An interesting study of the effect on the induced voltage and current, of variation of magnetic coup-

ling between the primary and secondary windings of an r-f interstage transformer is shown in Fig. 289:

Let coils L_3 and L_4 be so arranged that loose coupling exists between them, that is, L_3 is separated from L_4 so that only a small number of its lines of force link with L_4. If the tuning condenser is varied from zero to maximum capacity, we find that the induced voltage and current in the tuned circuit varies as shown by curve A, at the left of Fig. 290, having a maximum value at the resonant point. This curve has a sharp peak if the coupling is sufficiently loose, and the tuned circuit is therefore selective; in fact, it may be too selective.

If the coils are moved closer together to tighten the coupling, we might expect that as the field of coil L_3 linking with coil L_4 is stronger, the voltage and current in coil L_4 will be greater. This may be the case, but it is not necessarily so, especially if the coupling is greater than a certain "critical" value. The current induced in L_4 sets up its own magnetic field which tends to oppose any change in the inducing field of L_3 (Lenz's Law, see Art. 104), and this effect will be stronger the greater the current flowing in L_4. As the natural frequency of the L_4 tuned circuit is increased from minimum to maximum by the variable condenser, we find that as we approach the resonance frequency the current in L_4 *gradually* rises. As the current becomes stronger, the opposing field also increases correspondingly, reducing the effective or inducing field. As a matter of fact, a condition of sufficiently tight coupling will be reached where the current in L_4 will cease to increase, or actually decrease at the previous resonance point. The closer the two coils are placed together, the more marked will this effect be, as shown by curves B, C, and D, which represent successive degrees of tighter coupling. The double-humped curve D represents an extreme con-

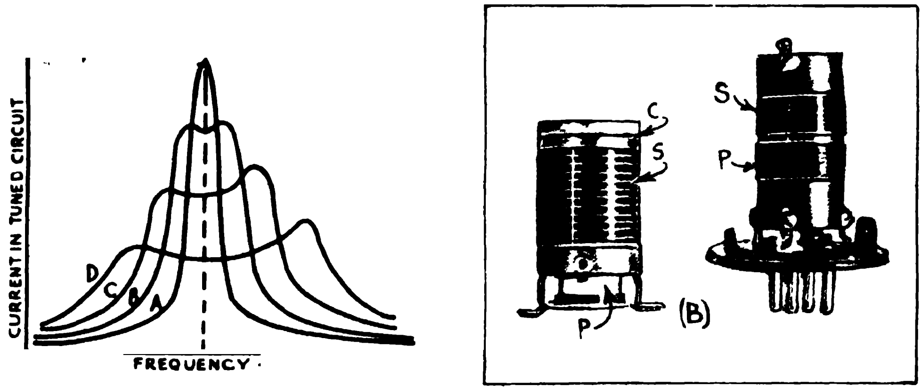


Fig. 290—Left: Effect of tightness of coupling, on the tuning curves of the secondary. Right: Typical r-f tuning coils used in screen-grid receivers. The one at the left has a high-impedance loosely-coupled primary P, a secondary S, and a capacity winding C That at the right, has a tightly-coupled primary. Both are only 1-inch in diameter

dition where there are two resonance points, that is, the same station is heard at two separated points on the dial. This of course is due to too tight coupling between the primary and secondary coils.

The question now arises as to just what proper value of coupling is necessary for best results. Let us consider L_3 and L_4 situated ten feet apart. Then since there is practically no linking of the magnetic field of L_3 with L_4, the coils have no effect on each other. If we now bring them together slowly we shall come to a point where the field of the primary links with the secondary, inducing a weak current in it. As the coils are brought closer together more and more of the magnetic field of L_3 links with

L_4, resulting in a gradual increase of induced voltage and current in the secondary. Finally, as the coils are brought still closer, the current in the secondary reaches such a value that it reacts seriously upon the primary, as we have described, causing the *effective* field to be reduced and the current weakened. The point where the secondary current no longer continues to increase as the coupling is tightened is called the point of "critical coupling". This is shown graphically at (B) of Fig. 289, where it is seen that as the coupling is increased from zero, the voltage and current in L_4 passes through a maximum value, and then decreases.

Therefore, for best results the coupling should be adjusted as near to the critical value as possible. Looser coupling than this results in poor transfer of energy, closer coupling results in poor selectivity, and also results in the secondary condenser tending to tune the primary coil through the agency of the reversed magnetic field. This tuning of the primary may result in oscillation tendencies due to the plate-grid capacitance of the tube. Notice, that the selectivity obtained is governed by something else besides the resistance of the tuned circuit, namely, the tightness of coupling between the primary and secondary. The calculation of the mutual inductance and coupling coefficient between coils was discussed in Articles 120 to 122.

405. Constant r-f coupling: A study of the coupling existing between the primary and secondary windings of an r-f transformer having a fixed primary, reveals the fact that for equal input, the voltage induced in the secondary is not constant over the broadcast frequency band. The induced r-f voltages in the secondary turns are proportional not only to the strength of the primary field, but also to the rapidity with which that field alternates. Thus at the higher frequencies, the r-f alternations are much faster than at the lower frequencies, and the induced r-f voltages will therefore be much greater when receiving stations around 200 meters than is the case when receiving stations around 500 meters. If such a circuit is made non-oscillating at 200 meters it has little sensitivity at 500 meters. If it is made sensitive at 500 meters by working near the oscillation point, it usually oscillates violently at lower wavelengths.

Several schemes have been developed to remedy this defect. In one, the Lord system, the primary coil is moved away from the secondary as the condenser is tuned to the higher frequencies. This is accomplished by a cam on the condenser shaft which acts on a follower attached to the primary coil. It is easily seen that the primary field, being removed from the secondary field at the higher frequencies, cuts a smaller number of secondary turns and thus induces less voltage.

In another, the King system, the primary is mounted on the condenser tuning shaft by an adjustable bracket and in such relation to the secondary coil that as the condenser is tuned to the low wavelengths the primary is rotated more and more at an angle with the secondary, thus loosening the coupling. In both these systems the plate load impedance remains substantially the same.

An arrangement credited to K. Hassel and used in Zenith receivers at one time, consists of taking a portion of the primary coil and mounting it on the condenser shaft so that it rotates inside of the secondary coil, in such a manner that the rotating portion of the primary coil opposes the coupling from the fixed portion at the low waves and adds to the coupling at the high waves. In this way the primary-second-

ary coupling is varied with change of wavelength and the impedance value of the load connected in the plate circuit of the tube is varied to keep it just below the critical value.

None of these systems are really simple enough for practical use in modern receivers where all of the tuned circuits must be operated by a single control. An electrical circuit method of automatically securing equal voltage transfer at all frequencies in the broadcast band is necessary. A system of this type developed by Messrs. Loftin and White, is based on the fact that the reactance of a condenser *increases* as the frequency de-

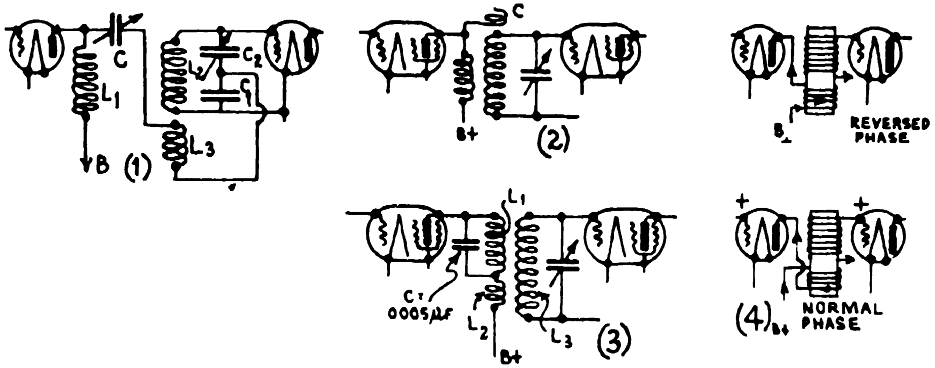


Fig. 290A.—(1) Loftin-White constant coupling circuit, (2) obtaining constant coupling by capacity winding C, (3) obtaining uniform amplification by resonated primary winding (4) primary and secondary coil connections

creases, and that the impedance of an inductance *decreases* as the frequency decreases (exactly the reverse).

The circuit of this system, one stage of which is shown at (1) in Fig. 290A, has its inductances and capacities so connected that there is both inductive and capacitive coupling. The values of the inductances and capacities are so adjusted that as the reactance of say the inductance starts to drop off, the reactance of the condenser increases, and vice versa, so that actually the coupling resistance remains almost constant for all frequencies within a reasonably wide band. Consequently, after the associated circuits have once been adjusted to prevent oscillation, there is no change in either the amount of selectivity, sensitivity or regeneration, at any frequency. By proper adjustment the set may also be made to oscillate at either the high or the low wavelengths.

In Fig. 290A it can be seen that inductive coupling is obtained through coils L_2 and L_3, while capacitive coupling is furnished by the condensers C and C_1. Coil L_1 is an r-f choke which prevents the leakage of any r-f currents into the "B" supply circuit, and makes them all go through L_3, through C_1 to the cathode, while C is a phase-shifting condenser which is employed for the purpose of shifting the phase of the r-f plate current.

Mutual inductance is less effective for transferring energy at the higher wavelengths than at the shorter ones. Mutual capacity behaves in an opposite manner. Suppose that the set is tuned to a low wavelength and all constants are adjusted to keep the receiver at maximum efficiency. Now suppose it is tuned to a higher wavelength. The energy transfer from L_2 to L_3 by inductive coupling decreases. Also as the tuning condenser C_2 is increased n capacity for tuning to the longer wavelength, its reactance decreases, and the voltage drop across it decreases. Therefore, there is more voltage across C_1 proportionately, and hence more current is fed to the tuned circuit by the capacitive coupling, offsetting the effect of the decreased energy transfer by magnetic induction.

One of the objections to this circuit is that it is rather difficult to adjust all of these parts when the receiver is built. It is not very well suited to quantity production methods of manufacture.

In r-f coils employing high-inductance primaries, the primary inductance is usually great enough so that in combination with all stray capacities across it, it tunes to some frequency below the broadcast band (a wavelength above 550 meters). This gives rise to the peculiar effect of the gain being good at around 550 kc, but poor around 1,500 kc. The falling off at the high frequencies can be partly compensated for by placing the primary (which is really a small choke coil in this case), at the grid end of the secondary and thereby introducing capacity coupling due to the difference of potential between the primary and the grid end of the secondary. This capacity coupling is of course more effective at the high frequencies, and by careful designing, a transformer may be obtained producing almost even amplification over the broadcast band. Another way of accomplishing this is to wind one or two turns of wire over the grid end of the primary. One end is left disconnected and the other end is connected to the primary. These few turns of wire then act as a small condenser between the primary and secondary, and by shifting them slightly along the coil, the value of this coupling capacity may be varied until best operation is obtained. This open-end "capacity winding" is marked C in the coil at (B) of Fig. 290. It is also shown at (2) of Fig. 290A.

A simple circuit scheme for obtaining uniform r-f amplification, and which has been used in many receivers employing screen-grid r-f tubes is shown at (3) of Fig. 290A. Here the primary L_2 and secondary L_3 form an ordinary r-f transformer. L_1 is a separate high-inductance coil wound to fit inside of the secondary at the grid end. A condenser C connected across it, tunes it rather broadly to resonance at whatever small band of frequencies it is designed to raise the sensitivity. Since this is a parallel tuned circuit, it acts as a high impedance load in the plate circuit at these frequencies, and so results in greater effective amplification by the tube at that particular band of frequencies. In this way, the sensitivity of the receiver may be increased at any frequencies desired.

Confusion often arises when connecting the primary and secondary windings of an r-f transformer to the two tubes between which it operates. There are two possible directions in which each winding may be connected. One arrangement is called "normal phase" and the other is called "reversed phase". Let us first assume that the primary and secondary coils are wound in the same direction of rotation as shown at (4) of Fig. 290A. This is generally the case; for the same winding machine winds both the primary and the secondary. In this case the plate of the preceeding tube is always connected to the end of the primary which corresponds to the cathode end of the secondary, when a *normal phase* connection is desired; the reverse is true when *reverse phase* is desired Both of these connections are shown at (4).

With the normal phase connection, if the grid of the preceeding tube is made say, more positive, an increase in plate current results. This increased plate current flowing through the primary winding induces a voltage in the secondary in such a direction as to tend to oppose this increase, (Lenz's law). This will make the grid of this tube more positive also, i.e., the signal impulses in the grids of the two tubes are in phase. With the reversed phase connection, the signal impulse on the grids of the two tubes is 180 degrees out of phase. When the coil is used with an oscillator tube, the plate and B+ ends of the primary go to the same tube. If the two windings are in opposite directions, the same rule applies, only the terminal connections of either one of the windings must be reversed. The calculation of mutual inductance and coupling coefficient between coils was discussed in Articles 120 to 122.

406. Losses in tuning coils: Although extreme selectivity in the r-f amplifier is undesirable from the point of view of sideband frequency suppression, unless some compensation of the audio high note response is purposely introduced into the audio amplifier or loud speaker, it is usually advantageous to keep the resistance of the tuned circuits as low as possible consistent with sensible, practical design, in order to obtain maximum voltage gain in the tuned circuits, and secure the proper amount of selectivity by proper coupling of the primary and secondary coils. Common sense should rule all attempts to reduce the resistance. It is not necessary to resort to the use of gold or silver wire because of their better conductivity, or to wind the wire to be self supporting so as to eliminate the supporting form or tubing, nor is it necessary to hang the coils up by threads in order to eliminate metal supports. Such drastic practices cost more than the results they accomplish are worth. It has been found by many tests that the most efficient form of r-f tuning coil is one wound in loose basket-weave, or simple solenoid form, somewhat like the coils shown in Fig. 290, having a ratio of diameter to length of approximately 2.5, and wound with No. 20 to 26 wire. This proportion may be departed from over quite a wide range without seriously affecting the efficiency of the coil. Actually, in the coils used in radio work this ratio may be as low as 0.75 and still the coils perform well. Due to the necessity for compact construction, American designers have reverted to the use of small tuning coils around one inch in diameter, wound with enamel-covered wire.

In order to get the 100 or more turns of wire necessary for these coils when they are used with the standard .00035 mfd. tuning condensers on the broadcast band, and still keep the length of the coil small, wire of about No. 30 B. and S. gauge is used. The efficiency of coils of this construction does not depart greatly from that of the more efficient coils which might be built with larger wire, of larger diameter, etc., especially when we consider that the coils in modern compact receivers must be mounted close together, and must therefore be enclosed by metal shielding to prevent interaction of the magnetic fields.

The losses in a coil in which high-frequency currents flow are much greater than the simple "ohmic resistance" of the wire measured for direct current conditions. All of the losses in a tuning coil at radio frequencies are usually summed up and expressed as a single loss called the *a-c resist-*

ance of the coil. This is usually considered at the particular frequency at which the coil is being employed. While this is not technically correct, it has become the accepted practice, since the final effect of these losses is to reduce the current in the tuned circuit, just exactly as if the tuned circuit itself had no resistance and we inserted a resistor equal in value to this so-called "a-c resistance" into it.

One source of loss, known as the *skin effect*, is due to the fact that at the high frequencies the currents travel only over the surface or "skin" of the wire, thus making only a small proportion of the total cross-sectional area of the wire effective in carrying the current, thus increasing the resistance to the flow of the current.

When d-c flows through a wire, the electron flow is uniformly distributed throughout the entire cross-section of the wire, that is, there is as much current flow-

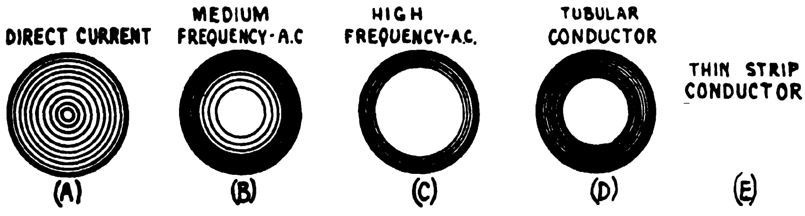


Fig. 291—Skin effect at high frequencies Due to the high self-induced counter e.m.f. developed in the center part of the conductor, the current flows only through a thin outside shell of the conductor at these very high frequencies

ing through a given area at the center as through an equal area near the outside surface, as shown at (A) of Fig. 291. When high-frequency a-c flows through a wire, the rapidly alternating circular magnetic field (magnetic whirls), produced around the wire (see Fig. 53), expands and collapses as the current rises and falls. This induces a counter-e. m. f. in the wire itself which tends to oppose the flow of current through it (Lenz's law). Since the field is varying most rapidly at the instants when the current goes through its zero values, during each half cycle (see Article 160), the induced counter-e. m. f. is greatest at these instants. But at these instants the magnetic whirls have either just collapsed to the center axis of the wire or are just about to spread out from there. Therefore the region of greatest counter-e. m. f. due to the field lies at the center axis and the current flow is opposed more there than at the outside regions. As the frequency is increased, the field varies rapidly even at other parts of the cycle, so the counter-e. m. f. becomes appreciable at these other times also. The result is, that at high frequencies a large proportion of the current flowing through the wire flows through the part nearest the outside surface, i.e., along a "surface shell" of the wire, as shown at (B) and (C). Therefore the conductor offers just as much resistance as it would if it had less cross-section area, i.e., the resistance is increased because the current or electron flow is crowded into a smaller cross-section area. The higher the frequency, the greater is the "skin effect". At very high frequencies, for a given weight of conductor we actually obtain better conductivity with a hollow tube having thin walls than from a solid wire, because the center of the wire only adds to the weight and cost of the conductor without serving any purpose in carrying current. If it is left out, it is not counted as part of the cross-section area and so the resistance is lower. The added resistance due to the skin effect is greater in larger wires than in small ones because in the larger wires less of the total bulk is represented by the skin or surface, so a smaller proportion of the whole bulk of the wire is being used to carry the current. A special wire called "litzendraht" has a very low skin-effect, due to the fact that it is made of 25 or more strands of fine wire each insulated individually from the others by enamel or cotton insulation. This is more expensive than ordinary magnet wire.

At broadcast frequencies (500 to 1,500 kc) the skin effect is not large enough to warrant the use of any special forms of wire for ordinary purposes. In short wave work (high frequencies) "Litz" wire is often used for receiver tuning coils. Transmitter tuning coils are usually made of copper tubing as at (D) or of thin flat-copper strip as at (E), to obtain a large surface area.

Another loss which exists in coils used in high-frequency circuits, is that due to eddy currents set up in the wires of the coil by the varying magnetic field. This increases as the diameter of the wire used is increased. The total resistance of r-f coils increases greatly as the frequency is increased. The amount of resistance increase depends on the shape of coil and size of wire. For instance, a single-layer solenoid coil of 300 microhenries inductance, consisting of about 58 turns of No. 28 D. C. C. (double cotton covered) wire wound on a 3-inch diameter tube, was measured and found to have a resistance of 3.15 ohms on direct current, 6 ohms at 500 kilocycles (600 meters), 10 ohms at 1,000 kilocycles (300 meters) and 14 ohms at 1,500 kilocycles (200 meters). When a coil is surrounded by metal shielding a loss also occurs due to the eddy currents set up in the shielding by the magnetic field of the coil. This will be studied in detail in Articles 412 and 413.

407. Distributed capacity: Another tuning coil characteristic which is usually undesirable, is known as *distributed capacity.* In a coil which has a potential difference existing between its terminals, a proportionate potential difference exists between every two adjacent turns of wire on the coil. Since the various turns of wire are conducting surfaces separated by the insulation on the wire, they form tiny condensers distributed along the turns of wire. As the adjacent turns are at different electrical potentials, small alternating currents flow back and forth in the tiny circuits formed by these distributed condensers at high frequencies. By imagining all the little distributed capacities of these condensers lumped together to form a single condenser C_D, the coil may be considered as a pure inductance with a condenser C_D in parallel. At low frequencies, the condenser effect is negligible and all the current flows through the wire. However, if the frequency is progressively increased, the reactance of the inductive part of the coil increases and that of the distributed capacity decreases, until a point is reached where practically all of the current passes through the distributed capacity, and the coil behaves like a condenser instead of an inductance. The working frequency-range of a tuning coil must be necessarily small if it is to have constant inductance. Since there are losses in these small condensers due to the imperfect insulation properties of the solid insulating material between the turns, and due to the dielectric hysteresis and absorption (see Articles 130 and 131), the apparent resistance of the coil is increased by their presence.

It is for this reason that tuning coils should not be coated with shellac and other "dope" preparations which increase the distributed capacity

effect and also the losses. Distributed capacity in a tuning coil is also a disadvantage, since it lowers the frequency range over which a coil can be tuned by an external condenser; for even when the external condenser is at its minimum value, the full distributed capacity is shunting the coil. If high inductance values, necessitating the use of a large number of turns of wire wound in several layers are necessary, the windings should be bank-wound as at f and g of Fig. 292, to reduce the distributed capacity.

Just as the capacity of a condenser may be decreased by decreasing the area of the plates or increasing the distance between them, the distributed capacity of a coil can be reduced by using a smaller wire or by

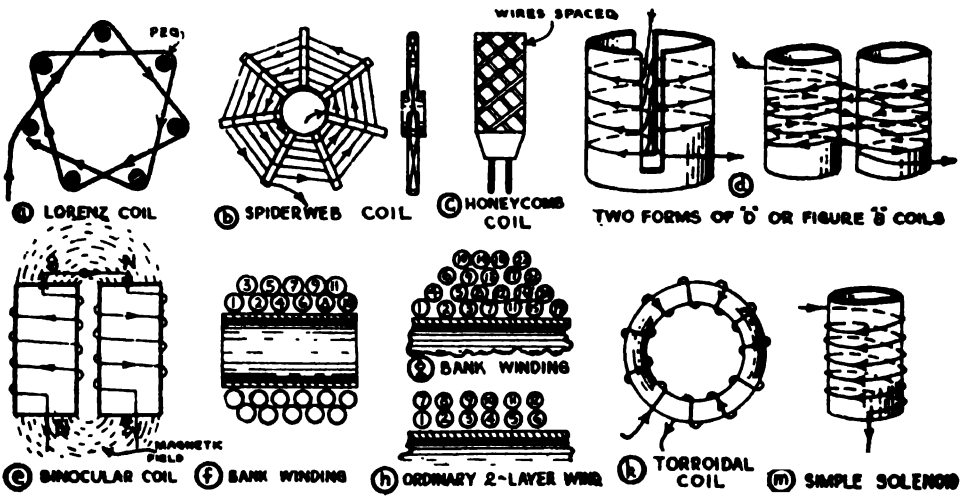


Fig. 292—Various shapes of coils and forms of windings which have been employed for r-f coils Those at (C), (G), and (M), are most popular now.

leaving a space between the adjacent turns of a coil. The size of the wire cannot be decreased too much, for the resistance will then increase, and the distance between turns cannot be made too large, for the inductance will then be decreased, necessitating more turns for a given value with consequent increased resistance and added capacity. On a solenoid, cotton covered wire of about No. 24 B. & S. gauge wound tightly, already has enough spacing between the metal of the conductors due to the double thickness of the insulation so that the turns may be wound close together. When enameled wire is used, a spacing equal to half the diameter of the wire may be employed to reduce the distributed capacity. The wire is usually wound in a spiral groove, machine-cut lightly into the coil form. This gives accurate spacing. It is obvious that the distributed capacity increases with the diameter of the coil, since this increases the effective surface area. This is another advantage in using small tuning coils.

408. Coil shapes and types of windings: Many shapes of coils and types of windings have been developed and used, but the fact remains

that for a given inductance value, the simple solenoid at (m), or the loose basket-weave coil at (a), have the lowest resistance of all of them when the diameter of the winding is approximately 2.5 times the length of the winding. This proportion may be departed from over quite a long range without seriously affecting the efficiency of the coil. Actually, in coils used in most radio work this ratio may be as low as 0.75 and still the coils perform well. However, each of the other forms of coils shown, have some particular advantageous feature which may make it particularly desirable for some special application. For coils having large inductance, the honeycomb or "universal" type winding is preferable on account of its compact form and low distributed capacitance. A discussion of various coil windings which have been developed follows. The various windings are shown in Fig. 292.

Lorenz developed a coil having a low distributed capacity. By winding the wire on a series of pegs arranged in a circle, he was able to zigzag it as shown at (a). No two turns are parallel to each other at close proximity for any distance, so the distributed capacity is lower than in the simple solenoid winding at (m). The pegs are removed after winding. Another way of reducing capacity is by winding the coils on flat strips mounted radially like the spokes of a wheel as at (b), and zigzagging the wire. This is known as the *spiderweb coil.*

The *honeycomb coil* at (c) is wound with a number of layers, the turns of each adjacent layer crossing each other almost at right angles. It is used where large values of inductance are required. It is usually mounted on a base having two contact pins for plugging into a receptacle. This construction reduces the distributed capacity. This is probably the most popular type of coil for long-wave reception, and for the intermediate-frequency amplifiers of superheterodynes. The so-called "universal" winding often used, is somewhat similar to this honeycomb type. These coils are made in various standard sizes, with inductance values, distributed capacity, etc., as given in the accompanying table.

DATA ON HONEYCOMB COILS

No. of Turns	Inductance at 800 Cycles, in Milli-henries	Natural Wave-length Meters	Distri-buted Capacity in Mmfd.	Wavelength Range, Meters 0.0005-Mfd. Condenser	Wavelength Range, Meters 0.001-Mfd. Condenser
25	.039	65	30	120 to 245	120 to 355
35	.0717	92	33	160 to 335	160 to 480
50	.149	128	31	220 to 485	220 to 690
75	.325	172	26	340 to 715	340 to 1020
100	.555	218	24	430 to 930	430 to 1330
150	1.30	282	17	680 to 1410	680 to 2060
200	2.31	358	16	900 to 1880	900 to 2700
249	3.67	442	15	1100 to 2370	1000 to 3410
300	5.35	535	17	1400 to 2870	1400 to 4120
400	9.62	656	13	1800 to 3830	1800 to 5500
500	15.5	836	13	2300 to 4870	2300 to 7000
600	21.6	1045	14	2800 to 5700	2800 to 8200
750	34.2	1300	14	3500 to 7200	3500 to 10400
1000	61	1700	13	4700 to 9600	4700 to 13800
1250	102.5	2010	11	6000 to 12500	6000 to 18000
1500	155	2710	13	7500 to 15400	7500 to 22100

The manufacturer's type numbers of commercial coils of this kind usually give a key to the number of turns they contain. Thus a DL25 coil has 25 turns, a DL100 coil has 100 turns, etc.

The illustration at (d) shows a D or "figure 8" coil, so called because each of its two halves form the letter D, and the whole coil forms a figure 8. It is wound by slotting a tube, or may consist of two separate interconnected coils as shown at the right. The magnetic fields of the two coils aid each other inside the tube and oppose each other outside so that a very small external magnetic field is produced. This reduces stray magnetic coupling with other coils in the receiver.

A *binocular coil* is shown at (e). This consists of two separate coils connected in series, and having magnetic fields as shown. This also has a very restricted external magnetic field, is easier to construct and is more efficient than the D coil.

A two-layer bank-wound coil as shown at (f), and (g) shows one of 4-layers. This type of winding is also used where a large inductance is required in compact form with low distributed capacity. The reason for banking the turns of a multilayer coil lies in the fact that the capacitance between layers of the ordinary multilayered solenoid is excessive. This capacitance gives the coil a tendency to oscillate at some particular frequency and moreover increases the dielectric losses. In banked coils instead of winding on one complete layer followed by successive similar layers, one turn is wound successively in each of the layers. The voltage between adjacent wires is thus reduced, and accordingly the distributed capacitance is reduced. This decreases the currents flowing in the tiny distributed capacity circuits. Compare the banked windings at (f) and (g) with the ordinary 2-layer winding at (h). For banked windings not too great in depth as compared to diameter, a close approximation for the inductance is obtained by using Nxn for the turns per inch in the solenoid inductance formula, (where N=No. of banks). The formula then becomes $L=.0251\ d^2 N^2 n^2 lK$.

A torroidal coil is shown at (k). This has the advantage of having practically no external field, but the resistance of this form of coil for a given inductance value is so high compared to that of the other forms that it is rarely employed in radio equipment.

While these and many other forms of coils have been developed for special purposes, the fact remains that for a given amount of inductance (within the broadcast frequency range) the most efficient coil is one of simple solenoid form as shown at (m), having a ratio of diameter to length of about 2.5. This ratio can be reduced to about 1 or even 0.75, without seriously affecting the efficiency. On broadcast frequencies it makes little difference whether the coil is self-supporting or whether it is wound on a thin insulating form. The latter is preferable for its mechanical rigidity. It is not necessary to use wire larger than about 24 B. & S. gauge. No. 26 or 28 can be used satisfactorily. (See Technologic Paper No. 298 of Bureau of Standards.) Now it is evident that for practical reasons, coils must be made of a definite size and of proper rigidity. Since the position of nearby metallic objects causes losses due to absorption of energy due to the setting up of eddy currents; and interstage coupling is undesirable, the tuning coils used in modern radio receivers are much smaller in physical size than were those used several years ago, because our receivers are made much more compactly now than they were then (see Fig. 286). The illustration in Fig. 293 show this interesting historical development and constant reduction in dimensions of tuning coils. At the left, is a large 4½ inch diameter coil popular in the neutrodyne receivers used as late as 1929. A smaller 2½" coil popular at about the same time is next. Following this is a 2-inch diameter coil, popular in 1929 and 1930. The small one inch coil at the right is typical of the type used extensively now, on account of its small size and limited external magnetic field. This illustration shows the exact comparative sizes,

since all of the coils were photographed together. The inch-scale alongside of the 3-inch coil shows the comparative sizes. Precision coil-winding machinery has been developed to wind r-f coils so they are produced by the thousands, with electrical constants suitably uniform. Enamel covered copper wire is used extensively on account of its obvious advantages of being handled without damaging by finger marks, and being unaffected by atmospheric moisture.

409. Interstage coil coupling: In Article 308 we found that any voltage induced in the grid circuit by means of energy fed back from the

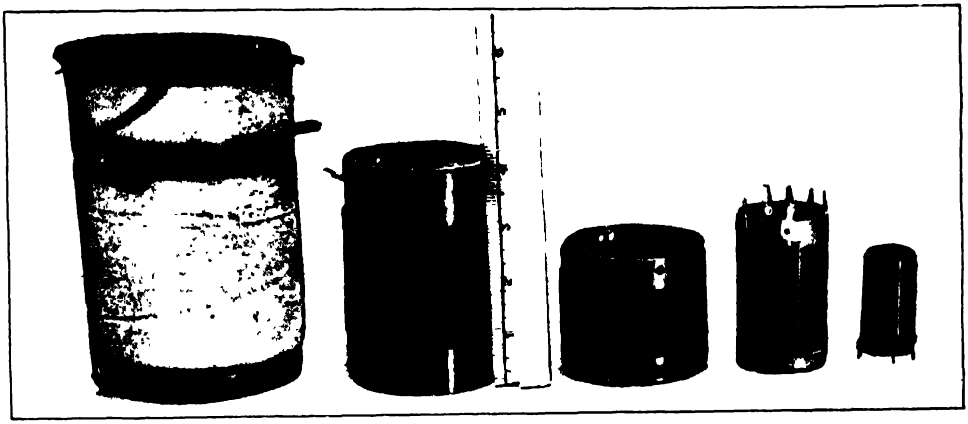


Fig. 293—This illustration shows how the dimensions of tuning coils have been reduced during the past few years. At the left is a 4½ inch diameter coil popular in 1923. At the right is a 1-inch diameter coil popular for use in modern receivers.

plate circuit of an r-f amplifier tube, would cause oscillation if it were of sufficient magnitude and proper phase relation. We found that the grid-plate capacitance of the tube was a prolific source of such feedback, and that special means for reducing or neutralizing this feedback were necessary if 3-electrode tubes were used as r-f amplifiers, on account of the comparatively large plate-grid capacitance of these tubes. The use of screen-grid type tubes removes the necessity for using these neutralization and losser schemes, since the feedback due to the p-g capacitance is very low because of the low value of this capacitance in tubes of this kind. However, feedback via the p-g capacity is not the only way in which it can take place. Energy can be fed back from the plate circuit to the grid circuit of any amplifier stage through magnetic coupling which may exist due to large stray magnetic fields, or close placement of the tuning coils. Energy may even be fed back from an r-f stage to a circuit one or two stages ahead of it in the receiver, through magnetic or capacative coupling. This fact is often overlooked by amateur set builders, with the result that despite elaborate precautions to eliminate oscillation, by using screen-grid r-f amplifier tubes, etc., persistent oscillations result due to

magnetic feedback between the tuning coils, or coupling in the B power supply, etc. If the fed-back energy is in phase with the incoming signal voltages in the grid circuit of that tube, increased response will result due to the additional amplification produced, but if it is large enough, as it usually is, it will cause the tube to generate oscillations, acting as an r-f oscillator. Whistling due to beat notes will be heard when a station is tuned in, or when the tuned stages are not set exactly at the frequency of the incoming signal. If the induced voltages due to feedback are out of

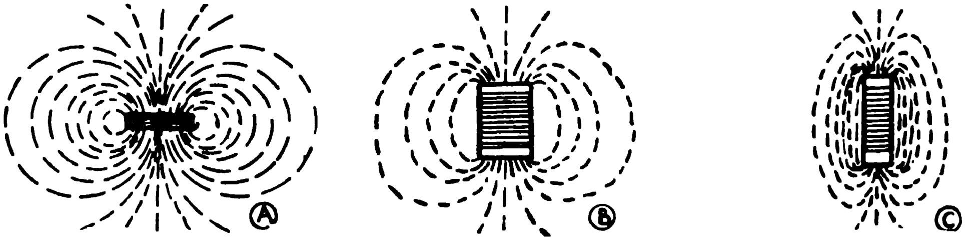


Fig 294—The proportions of a solenoid coil greatly affect the external magnetic field. The short, large-diameter coil of (A) has a widespread field, that at (B) has a more confined field, and the long thin coil at (C) has a limited external field, making it desirable for use in compactly built receivers.

phase with the incoming signal voltages, opposition or "degeneration" will result, and the response of the set will be decreased. As r-f amplifiers of higher and higher amplification per stage are built, any stray magnetic or capacitive couplings which may exist between certain parts or circuits become increasingly important, because the fed-back energy is amplified more by the tube, and there is greater tendency to cause the r-f tubes to go into the state of oscillation.

It is not necessary to eliminate every trace of feedback or coupling, for a small amount is desirable and is often purposely introduced by receiver designers because it increases the sensitivity of the receiver due to the additional amplification produced. It is when the feedback reaches a value sufficiently great to cause oscillation or cause the set to operate on the verge of oscillation, that it is objectionable. The stray couplings may be one or more of three types, magnetic, capacity, or resistance coupling. The latter is the most prevalent in B— power supply units and in grid-bias resistors connected in the common cathode return circuit for supplying grid bias for several r-f tubes. The remedy for each of these, is to use by-pass condensers of sufficiently large capacitance across the resistors in which coupling occurs, as explained in Article 377. Inductive coupling between wires and between coils was discussed in Articles 121 to 125. Objectionable capacitive and inductive coupling between circuits is best reduced by laying out the wiring of the receiver so that all *grid* and *plate* connecting wires are as short and as far apart as possible, preferably with air (dielectric constant=1) between them. If they must be run close due to the particular design of the receiver, they should cross at *right angles* if possible. Coupling between the successive tuning coils may take place through the medium of their magnetic fields. This is by far the

most prevalent form of coupling, but fortunately it can be almost entirely eliminated by proper design. The first precaution to eliminate magnetic coil coupling is to use coils having limited external magnetic fields. The torroid, D coil, binocular coil, etc., possess this characteristic, but these coils all have a much greater r-f resistance for a given inductance than the simple solenoid coil, so they are not used extensively. Satisfactory characteristics may be obtained by proper use of the more efficient solenoid form of coil.

410. R-F coil proportions: The shape of the magnetic field around a solenoid coil changes as the proportions of the coil are changed, as shown in Fig. 294. The field around a short coil of large diameter, is shown at (A). The field is nearly circular in shape, and extends out a large distance on all sides of the coil, obviously very good for interstage feedback coupling. A coil slightly longer than it is wide is shown at (B). The field is slightly elliptical in shape and does not extend out as far from the sides of the coil as the other. A long coil of small diameter is shown at (C). The field is very elliptical and does not extend far out from the coil. This is obviously the type of coil most suitable for use in compactly built radio receivers. Many of the commercial sets employ coils of this type having a diameter of about 1 inch and length of about 2 inches as shown in Fig. 290. They are wound with about No. 30 enameled wire, space-wound in a shallow spiral groove machine-cut in the coil form.

411. Placement of r-f coils: Even though r-f coils with limited external magnetic fields are employed, they must be mounted so close together in modern receivers of compact construction, that magnetic coupling between them must be eliminated either by mounting them in angular relation with each other in "no-coupling" positions, or else shielding them in metallic shields.

If the coils are all mounted with their axis lying in the same straight line, and turned so every coil is at right angles to every other coil, no magnetic coupling will exist between them. Fig. 295 shows this relation for three coils. Consider the magnetic field of coil B having a direction as shown by the arrows, at some particular instant. It links with coils A and C. Any line of force approaching the coil A from the right, cuts the wire twice and sets up a voltage in each half of every turn. These voltages are in opposite directions as shown by the arrows, and since they are equal, they neutralize each other. Hence there is no coupling to A. Similar reasoning holds for coil C, where the opposing directions of the induced voltages are shown. This

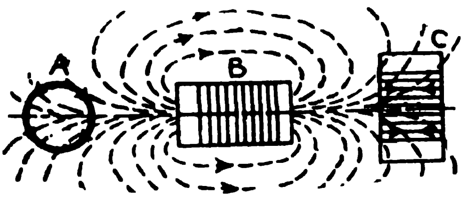


Fig. 295—Right angle coil placement to prevent magnetic coupling between coils. Axes of all coils lie along the same line.

right-angled placement of coils is simple and effective and has been used extensively in tuned r-f sets.

Another method is to place the coils parallel to each other but at such distances apart that the lines of force of each coil cut through the other coils at right angles to the axis, thus producing equal and opposite voltages in both halves of each turn, which neutralize each other. This is shown in Fig. 296. If the coils are mounted on a panel, in the manner shown at (A) to save space, it is found that the coils make angles A with

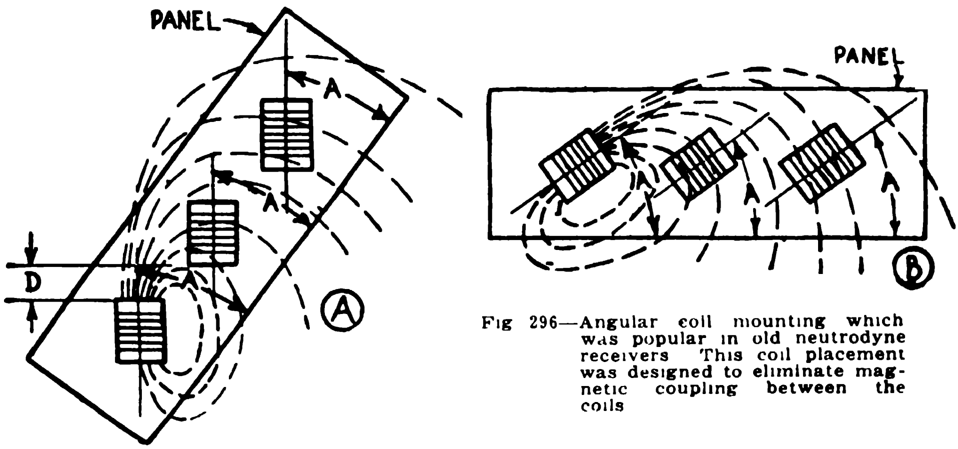


Fig 296—Angular coil mounting which was popular in old neutrodyne receivers This coil placement was designed to eliminate magnetic coupling between the coils

the base of the panel. If this panel is shown in a horizontal position as at (B) you will probably recognize the familiar neutrodyne arrangement used extensively several years ago.

Obviously the angle A at which the coils must be placed, and the distance D between them, are not constant factors for all receiver designs but vary with the physical proportions of the coils used, since the shape of the magnetic fields also vary with these. Consequently, although 54.7 degrees was recommended for the no-coupling angle A in the old neutrodyne sets, it does not follow that this angle is correct when coils of different size are used. The angle must be determined for the particular coils used. This makes the right-angle placement, discussed previously, more practical for ordinary use unless metal coil shielding is to be employed.

412. Shielding in r-f amplifiers: The coil arrangements just discussed, will eliminate magnetic coupling between various coils in an r. f. amplifier but they do not eliminate the capacity coupling which will exist between the windings on one coil and those on adjacent coils. The windings really act like the plates of condensers with the air space between the coils as the dielectric. When the coils must be mounted closely together, this capacity coupling will be very great. Both the interstage magnetic coupling and capacity coupling may be reduced greatly by enclosing the coils, or the entire separate r-f stages, in metal shields made usually of

aluminum or copper and connected to B— and ground. The energy of any stray magnetic fields, is dissipated in the shield metal in the form of heat, due to the fact that the rapidly alternating fields set up "eddy currents" in it (see (F) of Fig. 79). However, shielding introduces resistance into the tuned circuits due to the losses, unless great care is taken in allowing proper clearance between the coils and the shields.

A grounded plate or screen of fairly good conducting material enclosing the circuits under consideration takes care of the disturbing effects of *electrostatic fields* (see Article 309 and (A) and (B) of Fig. 225). As long as the metal enclosing the circuits is a good conductor, it may be thin and yet give complete shielding from external electric fields. If the resistance of the shielding material is very high, or if the frequency is quite high, the electrostatic shielding will be correspondingly less complete. For this reason, sheet iron, zinc, etc., are not good shielding materials for use in r-f amplifiers. It is a much more difficult problem, however, to eliminate the disturbing effects of the electromagnetic fields upon the circuits. To completely shield a space, it must be surrounded by a box of conducting material.

The question naturally arises as to the shielding efficiency of various metals. The basic factors governing the shielding efficiency of copper and brass in particular, have been investigated by Morecroft and Turner (Proc. Inst. Radio Eng. *13*, 477, 1925), while Mason (Q. S. T. *15*, 23, 1928) has measured and discussed the shielding efficiency of aluminum in reference to other materials such as copper and brass. It was found that the thickness of the shield, the frequency of the field which is being shielded and the conductivity of the shielding metal all have a bearing on the efficiency of the shielding. At low frequencies the thickness of the shield and the conductivity of the metal are relatively important factors. At the radio-frequencies used in broadcasting and at higher frequencies, however, the conductivity of the shield is not so important; very thin shields of either aluminum or copper may give practically 100 per cent shielding. Shields made of 20 gage (0.032 inch) or thicker aluminum sheet give good results mechanically and also give substantially 100 per cent shielding. This combination of high electrical conductivity, good mechanical rigidity and low weight has made the use of aluminum shielding very popular. Also it can be given a very pleasing and permanent dull silvery finish at very little cost. When copper is employed, it must be lacquered or otherwise treated to prevent corrosion and tarnishing.

Collapsable aluminum stage-shields are available with flat side pieces about 0.08 inch thick and special grooved corner pieces into which they fit. These are very convenient for making box-shields.

Shielding should be thoroughly grounded to the B– and ground circuits of the receiver. It is not considered good practice to employ the

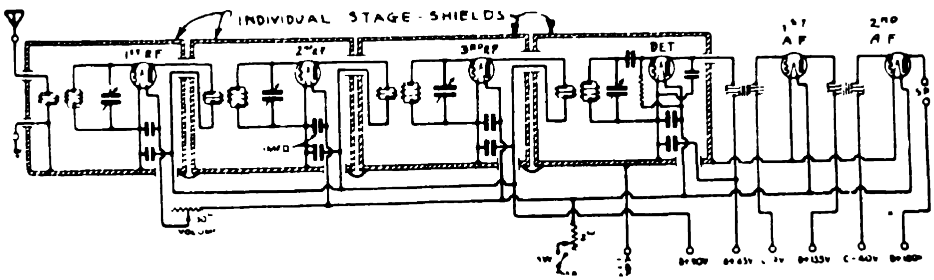
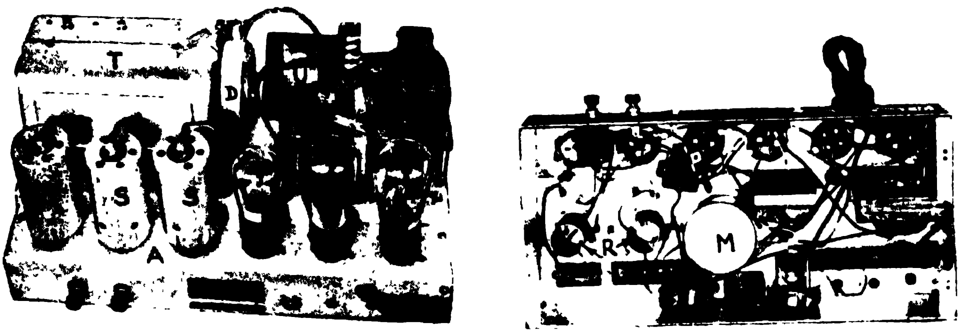


FIG. 297—Battery-operated receiver with three tuned r-f stages, in which each complete r-f stage and the detector, is shielded from the others by a separate metal enclosing "stage shield."

shielding as a conducting path for the filament, cathode, or grid return circuits, since undesirable couplings may take place between the various circuits due to high resistance joints in the path, or to the actions of the

magnetic fields of the returning currents. This is the cause of oscillations in many otherwise well-designed high-gain receivers, in which all other sources of interstage coupling have been removed. It is best to provide a separate insulated conducting wire for each current path. In this way the various currents are all confined to their proper paths and are kept separate. All holes in the shields, necessary for instrument shafts, wiring, etc., should be as small as possible, since the shielding effect can be



Courtesy Pilot Radio & Tube Corp.

Fig. 298—Top and bottom views of the chassis of a typical radio receiver in which individual tuning condenser, r-f tube, and r-f coil shields are employed. M is a coil shield.

totally spoiled by a few large open holes. Where wires are brought out through the shields, it is a good plan to use small rubber bushings to prevent abrasion of the insulation with resulting short circuits.

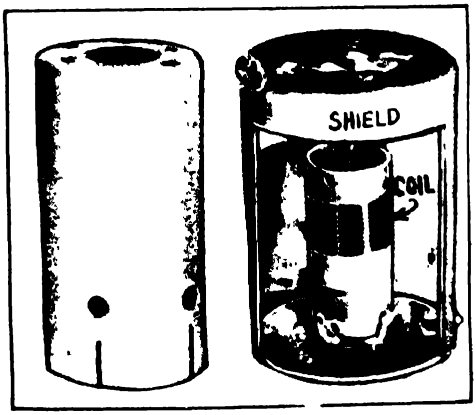
Considering the r-f amplifier of a receiver as a unit, the question arises as to whether to shield each r-f coil and tube individually or to shield each complete r-f stage consisting of wiring, coil, tube, and tuning condenser as a unit as shown in Fig. 297. Both methods can, and have been used. If the r-f amplifier parts are to be shielded individually, the coils may be enclosed in individual shield cans, (see Fig. 299) which can be made removable to facilitate testing and repairs. The screen-grid tubes can also be enclosed in separate removable shields of the type shown at the left. (The individual stator sections of modern gang tuning condensers are already shielded from each other by grounded electrostatic shield plates built into the condenser (see Fig. 268), so this source of electrostatic coupling is taken care of.) In this way, the necessary amount of shielding can be obtained at low cost, and the design is such that the entire chassis of the receiver is open and parts are easily accessible for test and repair work.

Rear and bottom views of the chassis of a typical receiver constructed in this way are shown in Fig. 298. At the left, the aluminum shields S on the three screen-grid r-f tubes are shown, the control grid caps of the tubes projecting through the rubber-insulated holes in the shields. Directly behind these is the shielded "gang type" tuning

condenser T, with its dial D, at the right. Next to this is the power pack, with its enclosing shield removed to show the power transformer U, choke V, etc. In the bottom view of the chassis, two of the r-f coils R, with their aluminum shields removed are shown at the left. Next to these is one of the coil-shields M in place over the third coil. Notice that the entire receiver construction is open, providing good ventilation and easy access to any part. At the left of Fig. 285 may be seen the shielded assembly of a typical intermediate-frequency transformer of a superheterodyne receiver. The entire unit with its two small mica compression-type tuning condensers is enclosed in the aluminum shield can.

The construction in which separate shields are used for complete r-f stages, is usually more expensive than the individual unit-shielding just described, since much more shielding metal must be used and the entire structure of the receiver is more complicated. Testing and repair work are hampered, since the stage shields must be taken apart and removed in order to get at the wiring and parts for such work. The only real advantage it possesses is, that since all wiring in the r-f stages is enclosed within these shields the wires cannot be acted upon by any strong fields from powerful local broadcasting stations and have signal voltages induced in them. This, of course, would reduce the selectivity of the receiver. A metal cover-plate underneath the chassis of the unit-shielded receiver would eliminate this effect however.

413. How shielding affects a tuning coil: One effect accompanying the shielding of a coil by means of a metal enclosing shield is shown in Fig. 299. A shield for a screen-grid tube is shown at the left. Next to it is an r-f coil enclosed in a shield can, cut open at the front to show the interior. As shown at the right, the windings on the coil and the metal of the shield form the plates of a condenser. This is a constant capacity



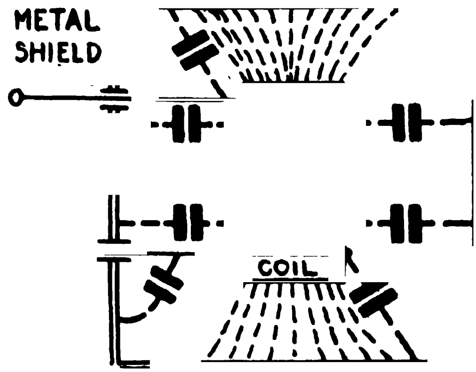


Fig. 299—Left: An aluminum shield for a screen-grid type r-f tube is shown at the left. Next to it is a shielded r-f coil with its shield cut open to show the interior. Right: How the shield around a coil adds to its distributed capacity and reduces effective tuning frequency or wavelength range of the coil.

and acts the same as the distributed capacity of the coil. It reduces the effective tuning range which may be obtained with any given tuning coil and condenser, acting like a small fixed capacity connected in parallel

with the tuning condenser, so that even when the tuning condenser capacity is at minimum value, this capacity is still in the circuit. As a result of this capacity action, a shielded coil to be used with a tuning condenser of given size should have a few turns of wire *less* than if the shield were not used. This effect is partly counteracted by the fact that since part of the magnetic field of the coil is absorbed by the shields, a reduction of the self-inductance of the primary coil results. This makes it necessary to use a few turns more on the coil to compensate for this reduction. However, if the coil is of small diameter and the shield is of such size that a space equal to at least the diameter of the coil separates the coil from the shield all around, the latter effect will be smaller than the capacity effect, with the net result that a few turns less than the normal number must be used when the shield is employed. The shield around a coil should always be made as large as possible, especially along the length of the coil, consistent with the space available for it. If insufficient space is left between the coil and shield, the distributed capacity of the coil is increased very greatly, reducing the tuning range. Also, excessive eddy currents will be produced in the shield metal due to the magnetic field of the coil. This is a loss, and acts as an increase in the a-c coil resistance. When using a shielded coil, the coil itself should first be designed with proper proportion of length and diameter which will give a small external field. Then the shield should be designed to confine this field as much as is necessary, without seriously increasing the a-c resistance of the coil.

414. General shielding considerations: Shielding is rarely necessary in well-designed *audio* amplifiers, unless a large number of stages of high-gain amplification is used. Even in r-f amplifiers, shielding should not be used indiscriminately, since it not only adds to the cost of the receiver and complicates the construction, but if not employed properly, no practical advantage will be obtained from it,—in fact, it may cause harmful absorption of energy.

With ordinary tubes in receivers using one stage of amplification and regenerative detector, since most of the energy is confined in the detector circuit, with comparatively small r-f currents flowing in the r-f amplifier, shielding is usually unnecessary if the coils are kept at right angles and a fair distance apart. In exceptional cases, a grounded plate-shield placed between the coils will be all that is necessary for shielding. With two stages of tuned r-f, shielding is not usually required if small coils placed at right angles a reasonable distance apart are used, and if wiring is done carefully unless the receiver design is very compact and the parts must be mounted very close together. A small grounded plate-shield between the transformers will usually suffice in many cases. In sets employing three or more stages of r-f amplification, it is almost always necessary to completely shield the individual stages of the entire r-f amplifier, if high amplification per-stage is to be obtained. All "A" and "B" power supply leads should be properly choked and bypassed to prevent r-f currents from the various stages from passing into the power supply device and causing interstage coupling there due to the various impedances encountered.

Wiring in a shielded set should be laid out carefully. Plate and grid leads and connections to neutralizing coils and condensers must be removed as far as possible from the metal, in order to minimize their capacity to ground, and thus minimize detuning effects. Grid and plate neutralizing connections that must be run from one shielded compartment to another should be carefully insulated from, and not run parallel to, the shields.

REVIEW QUESTIONS

1. What must be the inductance of the secondary coil of an r-f transformer if it is tuned with a condenser having a maximum capacitance of .0005 mfd? The maximum wavelength is to be 600 meters.
2. The tuning condensers across the primary and secondary windings of the band-pass intermediate coils in a 175 kc superheterodyne receiver are of 200 mmf. capacitance. What is the inductance of each coil, in microhenries, neglecting the distributed capacitance?
3. An inductance of 150 microhenries is to be tuned to 200 meters. What is the capacitance of the tuning condenser required?
4. A tuning coil in a long-wave receiver is to tune to 1200 meters with a tuning condenser of .0005 mfd. What must be the inductance of the coil? What standard size of honeycomb coil would you use for this?
5. If the coil in problem 1, is wound with No. 30 enameled wire on a one-inch diameter form, find the total number of turns required and the length of the winding. (The coil design charts may be used for this.)
6. Draw the circuit diagram for, and explain the operation of two simple methods designed to produce uniform amplification in a simple tuned r-f amplifier over the broadcast frequency band. What are the advantages and disadvantages of each?
7. Show how the primary and secondary windings of an r-f transformer should be connected between two tubes for *normal phase* connection; (a) if both windings are in the same direction; (b) if the windings are in opposite directions.
8. What is meant by the distributed capacity of a coil? Illustrate your answer with a sketch. What is the objection to high distributed capacity in a tuning coil? How may it be kept low?
9. Describe several types of inductance coils and state the advantages and disadvantages of each.
10. How may the coupling between the primary and secondary of a coil be tightened, loosened?
11. What is the effect on the tuning characteristic if excessively tight coupling is employed between the primary and secondary of a t-r-f transformer?
12. How may 3 coils be placed to prevent inductive coupling between them?
13. What is the purpose of shielding in r-f amplifiers and how does shielding accomplish this purpose?
14. What materials are suitable for shielding? Which is used most? Why?

15. State three ways in which energy feedback from the plate circuit to the grid circuit can take place in an r-f amplifier stage. Illustrate your answers with sketches.
16. Name three losses which exist in tuning coils and explain how the coil should be constructed to make each as small as possible.
17. What is meant by "skin effect"? What causes it? Why does it increase greatly as the frequency is increased?
18. Why is it desirable to use more turns of wire for the primary winding of an r-f transformer used with screen-grid tubes than for one used with '27 type three-electrode tubes?
19. The secondary of an r-f transformer tunes from 200 meters to 600 meters with a certain tuning condenser. An aluminum shield is put around the coil to prevent interstage coupling. Now the coil and condenser tune from above 600 meters down to a minimum of 250 meters. Explain the reason for this.
20. What must be done to the coil in problem 19 in order to permit tuning down to 200 meters when this coil-shield is used?
21. A tuning coil is to be designed with a tap so that when it is used with a tuning condenser having a maximum capacitance of .00035 mfd., maximum wavelengths of 600 and 400 meters may be reached by using either the full coil or the part from one end to the tap. Design the coil if it is to be wound with No. 26 D. C. C. wire on a 2 inch diameter form. Locate the exact position of the tap, neglecting any interaction due to the unused portion of the winding when the tap is employed.
22. To what minimum wavelength will the arrangement in question 21 tune both when the full coil is used and when the tap is employed, if the total of the distributed capacity and the minimum capacitance of the tuning condenser is .00004 mf?

CHAPTER 24

AUDIO AMPLIFICATION

NEED FOR AUDIO AMPLIFICATION — R-F VS. A-F AMPLIFICATION — REQUIREMENTS OF THE A-F AMPLIFIER — FREQUENCY RANGE DESIRED — IMPORTANT CHARACTERISTICS OF THE HUMAN EAR — POWER IN SOUNDS OF VARIOUS FREQUENCIES — VARIATION IN INTELLIGIBILITY OF SPEECH SOUNDS — COMPENSATING FOR SIDE-BAND SUPPRESSION — THE TRANSMISSION UNIT—DECIBEL — FREQUENCY RESPONSE CURVES — COUPLING METHODS — TRANSFORMER COUPLED A-F AMPLIFIER — DESIGN OF THE A-F TRANSFORMER — TRANSFORMER RATIO — LARGE SIZE TRANSFORMERS AND CORE SATURATION — PARALLEL-FEED PLATE SUPPLY — CLOUGH SYSTEM WITH RESONATED PRIMARY — RESISTANCE COUPLING — SIZES OF RESISTORS AND CONDENSERS — MOTORBOATING — CHARACTERISTICS OF RESISTANCE-COUPLED AMPLIFIERS — IMPEDANCE COUPLED A-F AMPLIFIER — AUTOFORMER IMPEDANCE COUPLING — DUAL-IMPEDANCE COUPLING — DIRECT COUPLED AMPLIFIER — THE LAST AUDIO STAGE — POWER TUBES — PUSH PULL AMPLIFICATION — PARALLEL OUTPUT TUBES — DISTORTION TESTS — MAXIMUM UNDISTORTED OUTPUT — MATCHING INPUT AND OUTPUT IMPEDANCE — DUAL PUSH PULL — TONE CONTROL — REVIEW QUESTIONS.

415. Need for audio amplification: Thus far we have studied the construction and operation of the various r-f amplifier and detector systems employed in radio receivers. The function of the r-f amplifier is to increase or amplify the amplitude of the weak signal voltages before they reach the detector. The current in the plate circuit of the detector (Figs. 236 and 237) varies at the audio frequencies of the sounds being transmitted. These current variations are usually too weak to operate a loudspeaker, and can be amplified again before reaching the loud speaker, by means of one or more vacuum tubes connected up suitably as amplifiers. Since the currents and voltages appearing after the detector vary at the audio frequencies of the sounds in the program, this is known as *audio-frequency* (a-f) amplification, and the amplifier is called an *audio-frequency* (a-f) amplifier.

This presents then, three choices of amplification of the incoming signal voltages, (1) the r-f signal can be amplified before reaching the detector by successive stages of r-f amplification; (2) it can be amplified after leaving the detector by successive stages of a-f amplification; (3) it can be amplified both before and after by a combination of the two, as shown in Fig. 300. It should be understood that the r-f amplifier may be

either of the t-r-f or superheterodyne type. A consideration of just what advantages and disadvantages can be secured by each of these methods is important at this time, as it will make clear the reasons for building radio receivers as we do, and the reasons for possible future changes. The question of the correct proportions of r-f and a-f amplification in a receiver is assuming great importance lately. A study of the advantages and practical limitations of each of these forms of amplification will help toward a clearer understanding of the receiver.

416. R-F vs. A-F amplification: Until recently, the use of detectors which operated on the square law principle was widespread. With

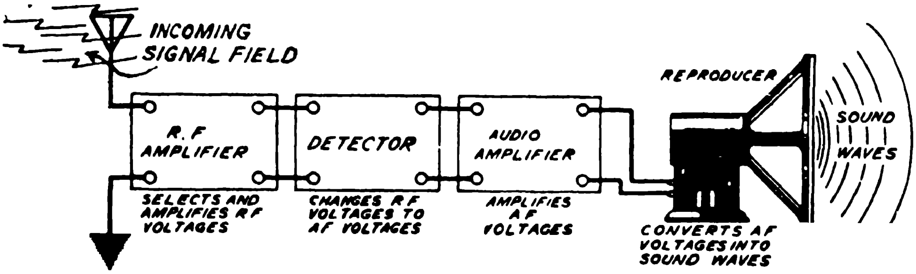


Fig. 300—Modern radio receiver system. The incoming radio-frequency signal voltages induced in the antenna, are tuned and amplified by the r-f amplifier, (which may be of the t-r-f or superheterodyne type); then they are detected or "demodulated", and the resulting a-f voltage variations are amplified further by the a-f amplifier, finally being converted into sound waves by the loud speaker

a detector of this type, since the detector output is approximately proportional to the *square* of the strength of the voltage variations applied to its input, up to a certain limit, the advantage of doing the amplifying in the r-f amplifier ahead of the detector is self-evident, since amplifying the signal voltage a certain amount before the detector, makes the actual gain proportional to the square of this increase, when considered in the detector output. This advantage no longer holds when linear detectors of the types now becoming popular are employed, because with this type of detector the detector output always bears a certain fixed ratio to the input, regardless of the amplitude of the input signal voltages.

A real important advantage of r-f amplification is that the function of tuning or signal selection can be combined with that of amplification in the r-f amplifier, whereas no station tuning or selective effect is obtained in the audio amplifier. Therefore, even if we built a receiver simply with a detector and many stages of audio amplification, we would still need several tuning circuits ahead of the detector to obtain the necessary selectivity (ability to eliminate the signals of unwanted stations). The tuning circuits cannot be eliminated, with our present radio transmitting and receiving system. The increased number and power of transmitting stations on the air is daily making the selectivity problem more and more acute. On the contrary, if we build our receiver with many stages of r-f

amplification and a detector (with no audio amplification) we have theoretically, all the requisites for a satisfactory, complete receiver, insofar as radio or television signals are concerned. The trouble with a system of this sort is that the detector tube must handle the full amplified signal voltage. There are no practical forms of detectors, (demodulators), available at the present time which are capable of handling signal voltages as large as would exist at the detector input of a receiver of this sort. Therefore a practical compromise is made in most commercial receivers by tuning and amplifying the incoming signal voltage in the r-f amplifier, to a value just below that which the detector can handle without overloading, then detecting or "demodulating" it by the detector tube and finally amplifying it further by one or two stages of audio amplification to the required strength necessary to satisfactorily operate the loud speaker. By using "power detectors", it is permissable to build up the signal voltage to quite some strength in the r-f amplifier before applying it to the detector, and therefore but one stage of audio amplification is required in most cases. This takes the form of a *power stage*, designed to deliver as much electrical "power" to the loud speaker for a given input signal voltage applied to its grid circuit, as possible.

Another disadvantage of employing much audio amplification lies in its ability to amplify all stray electrical disturbances which are of such frequency as to cause objectionable sounds in the loud speaker. Such circuit noises may be caused by low "A" or "B" batteries with consequent variation in supply voltage, hum due to incorrectly designed electric power supply units, loose connections, microphonic tubes, non-uniform emission along the length of the cathode, etc. These are all caused by electrical disturbances lying within the usual audio-frequency range and will of course be amplified by the audio amplifier because the a-f amplifier is actually designed to amplify voltage variations of such frequencies. This becomes especially important in a-c electrically-operated receivers, where slight 60 or 120 cycle voltages due to stray magnetic induction are amplified greatly, resulting in an objectionable low-pitched hum from the speaker. Such disturbances are not likely to cause as much trouble in an r-f amplifier because the r-f transformers do not efficiently transfer such low frequency variations from stage to stage.

It is possible to build r-f amplifiers, using screen-grid type tubes, to produce any desired amount of amplification. The old troubles due to feedback and oscillation caused by the plate-grid capacity of the amplifier tube, have been practically eliminated with this form of tube. As a matter of fact, r-f amplifiers of both the tuned r-f and superheterodyne type may be designed and constructed to produce so much amplification, that they may actually be useless for use under average reception conditions, due to amplification of all stray electrical disturbances picked up by the antenna circuit to such an extent that extremely "noisy" operation results. In other words, they may receive below the "noise level". Of course, this is an undesirable extreme.

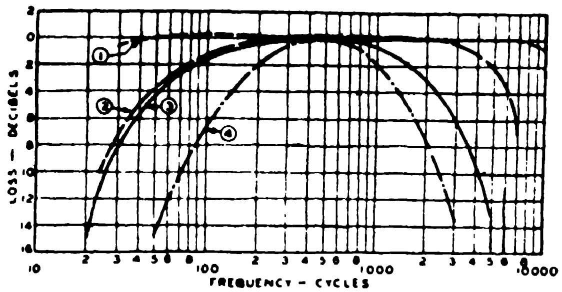
An advantage of a-f amplification lies in the fact that it is relatively easy to build a two-stage (and with care, a three-stage) a-f amplifier that is perfectly stable and gives high amplification. The amplifier noises mentioned are a disadvantage especially when more than two stages are used, but the production of better tubes and associated apparatus is reducing this objection. When a phonograph pickup is to be used in conjunction with the radio receiver, some audio amplification is necessary to strengthen the low output voltage of the pickup to a value sufficient to give satisfactory loud speaker operation. Since in such receivers, at least one stage of audio amplification must be provided for the phonograph pickup, it is also employed for amplifying the radio signal voltage, when radio programs are received.

A consideration of all these factors shows that the question of just how much r-f *or* a-f.; or r-f *and* a-f amplification it is best to employ must necessarily be decided by a compromise between all of the factors involved. In the old types of receivers employing 3-electrode tubes in the r-f amplifier it was almost standard practice to use at least two stages of a-f amplifica fon following the detector. In modern receivers in which screen-grid tubes are employed in high-gain r-f amplifiers and a power detector is employed, the signal voltage is built up to such high values in the r-f amplifier that but a single stage of audio amplification is required and used. Of course audio amplifiers find many other uses outside of radio receivers. They make public address systems possible, are used in home recording of phonograph records, in photo-electric cell operated devices, in sound pictures, etc., so it is essential that the various systems employed be thoroughly understood. While the general audio amplifier systems are applicable in many of these fields, in this chapter we will consider them particularly from the viewpoint of the radio receiver. The special characteristics required for public address work, television signal reception, sound motion pictures, etc., will be discussed in conjunction with these subjects later.

417. Requirements of the a-f amplifier: It is desirable that an amplifier employed to amplify the audio-frequency signal voltage output from the detector tube of a radio receiver, be looked upon not as a separate device, but as part of the entire receiver consisting of the r-f amplifier, detector, a-f amplifier and loud speaker. It should be kept constantly in mind that the prime object of the radio receiving apparatus taken as a unit, *is to reproduce faithfully, without noticeable change or distortion of any kind, the music or speech produced by the performers in the studio of the broadcasting station.* Notice that "*noticeable change*" was mentioned, because due to certain characteristics of the human ear, it is possible to have some changes take place without being noticed or detected by the average ear; that is, absolute perfection is not necessary. It is not always desirable to have the audio amplifier, amplify all frequencies within the audio range equally, for in many cases deficiencies in loud

speaker response, or even in the r-f amplifier or detector, can be equalized by an audio amplifier designed especially to over-amplify certain frequencies. It is desirable however, to have the amplifier amplify the incoming signal voltages without distortion of any kind in the wave-form.

418. Frequency-range desired: A detailed study of the characteristics of the various speech and musical sounds broadcast during radio programs was made in Chapter 2. We found that an audio-frequency range of from about 40 or 50 to 8,000 or 10,000 cycles is desirable for the transmission, reception and reproduction of speech and music. Radio



Courtesy Western Electric Co.

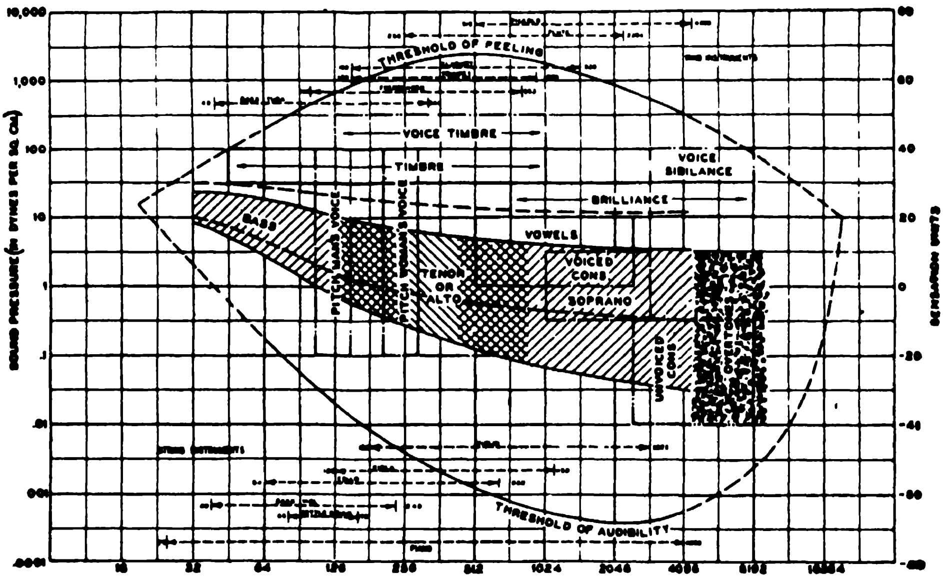
Fig 301—Comparison of average sound frequency transmission characteristics of radio transmitters and receivers of a few years ago with those of recent date are shown by these curves Curve (1) shows the audio frequency transmission characteristic of a modern broadcasting station

transmitter development has reached a stage where the apparatus may be designed to transmit almost any required range of sound frequencies. The performance of recent broadcasting equipment in transmitting the range of audible frequencies is indicated in Fig. 301. In this figure, (1) is the characteristic of the present Western Electric 50 kw. transmitter, (2) is that of the Western Electric 500 watt transmitter of 1924, and (3) and (4) are characteristics of typical radio receivers of the present and 1926, respectively. It is evident that the faithfulness of reproduction still depends largely upon the performance of the receiver, since the modern transmitters are capable of almost perfect quality in this respect. Notice the almost flat transmission curve between 40 and 10,000 cycles for the modern 50 Kw. transmitter. Although these are designed with a sound frequency-range up to 10,000 cycles, they do not actually broadcast anything above 5,000 cycles. This is due to the fact that there is but a 10,000 cycle (10 kc) band between adjacent station carrier-frequency assignments, and since both sidebands are broadcast, frequencies above 5,000 cycles begin to overlap those of the station on the next assignment. It would appear that 5,000 cycles is the extreme limit of reproduction to be hoped for without a wider separation of transmitting station channels.

In order to obtain true reproduction of speech and music, the entire radio receiving equipment including the sound reproducer taken as a unit, should not introduce or suppress any of the audio frequencies present in the signal, nor should they be partial to certain frequencies and amplify them more than they do others. True reproduction requires that all the original frequencies, fundamentals and overtones be present

in the same proportion as in the original sounds. Incidentally, the audio amplifier in a television receiver is called upon to amplify a much larger band of frequencies uniformly than that employed in a receiver for sound programs only.

419. Important characteristics of the human ear: When considering audio systems, some important characteristics of the human ear must also be considered. There is a minimum sound intensity below which the human ear cannot detect sounds and a maximum intensity above which sound becomes painful. These values vary with the frequency. At low levels of sound intensity, a change of about 25 per cent in loudness must



Courtesy Bell Telephone Laboratories

Fig. 302—Any sound wave that can be heard, lies within the field outlined here. Areas covered by the most prominent speech sounds are indicated both as to their frequency, range and sound pressure by the center shaded region. The threshold of audibility curve indicates the actual value of sound pressure required to just produce an audible sound at the various frequencies. The threshold of feeling curve indicates the sound pressures which produce the sensation of feeling or pain rather than of sound—at various frequencies.

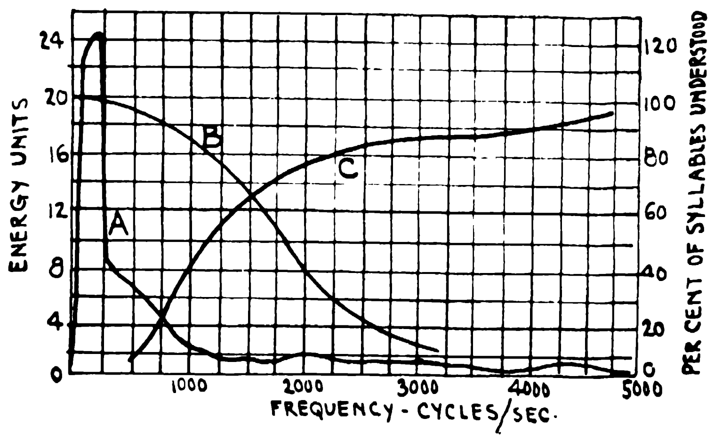
occur before it will be detected by the human ear. At greater intensities, the change must be at least 10 per cent before it will be noticed.

The range of pressure and frequency that the ear will respond to, is shown in Fig. 302, in which the scale of absicissas is frequencies in cycles per second, and the ordinate scale is sound pressure in dynes. Frequencies above about 20,000 cycles are not perceived as sound, nor are those below about 20. Any frequency between these limits, however, is recognized as sound if its pressure is above the lower boundary curve marked "Threshold of Audibility." The upper boundary, marked "Threshold of Feeling" indicates the pressure at which feeling begins. Above this line the sounds are felt, actually causing pain by their excessive pressure.

Frequency and pressure are only the physical characteristics of a sound; our mental responses are called pitch and loudness. Both of these vary logarithmically with their stimulas, difference in pitch between two sounds corresponding to the logarithm of the ratio of their frequencies, and similarly, differences in loudness are pro-

portional to the logarithm of the difference in pressure, but with loudness the proportionality is not quite constant so that constant loudness lines are not truly horizontal. Because of this logarithmic law the illustration is plotted with logarithmic scales, and in addition an arbitrary loudness scale is shown on the right, the units of which, called "sensation units", are defined as twenty times the logarithm of the pressure.

420. Power in sounds of various frequencies: Although sounds of different frequencies can be adjusted so they sound equally loud to the average human ear, the power required to produce these sounds differs widely. It has been determined experimentally by Dr. Harvey Fletcher and his associates at the Bell Telephone Laboratories, that the energy



Courtesy Bell Telephone Laboratories

Fig 303—Curve A shows how the *power* necessary to produce sounds of different frequencies but equal loudness, varies. Curve B shows how the intelligibility of speech sounds varies as all the frequnecies *below* the certain value are eliminated. Curve C shows how this varies as all the frequencies *above* the certain value are eliminated The scale at the right applies to these two curves.

necessary to produce speech sounds of the same intensity but of different frequencies, varies according to the curve A in Fig. 303 for the average human ear. It is evident that a very large increase in power is required to produce the sounds below about 500 cycles. Since the ear is very sensitive to tones around 1,000 cycles, very little energy is required to produce tones of this frequency for the same degree of loudness as shown by the sharp drop of curve A around 1,000 cycles. This curve is very important in the study of the "power" or "output stage" of audio amplifiers, for it shows that the loud speaker will require a much larger amount of power from the power tube for these frequencies than for the higher ones—provided it is capable of producing the lower-frequency sounds. An amplifier that can amplify the low frequencies requires a power tube and power supply system of larger rating, and more amplification, than another amplifier that does not amplify these low-frequency notes.

421. Variation in intelligibility of speech sounds: We have seen that the ear is able to perceive a large number of tones of different inten-

sity and frequency. We have also seen that the voice and various musical instruments produce tones which cover a large portion of the auditory sensation area. In order to obtain information as to the relative importance of various parts of this area to the sensory characteristics of speech and music, experiments have been performed in which the tones falling in various parts have been eliminated from the sounds by means of high-pass, low-pass and band-pass filters.

It has been found that if all of the frequencies below 100, 200, 300 or on up to 1,000 cycles are progressively eliminated from speech, it is still 85 per cent intelligible, though a greater part of the energy of the sounds has been removed as shown by curve A. Curve B of Fig. 303 shows the relation between the intelligibility of speech (per cent of words understood) and the elimination of all frequencies *below* a given frequency. The vertical scale for this is at the right.

However, although the sounds can be understood, the character or "tone quality" of the speech changes markedly. Due to this relative insensitivity of the ear, an average audio amplifier and loud speaker can be built with a rather poor audio characteristic and still sound reasonably good to the average ear. Although the ear can understand those sounds which lack the lower tones, listening to an amplifier and reproducer of this kind is very tiring and irritating.

When frequencies above 8000, 7000, or on down to 3000 cycles are eliminated, the character of the speech again changes markedly. The term "sibilance", appearing to describe best the characteristic lost, refers to the prominence of the hissing or frictional character of speech. If attention is directed to such sounds as s, f, th, and z, the elimination of frequencies above 6000 or 7000 cycles is readily detectable, but it requires rather close attention to detect the elimination of frequencies above 8000 cycles. Curve C of Fig. 303 shows the relation between intelligibility and the elimination of all frequencies *above* a given value. As will be seen from this curve, if the frequencies above 1,000 cycles are omitted, only 40 per cent of the speech sounds will be understood. Although the sounds may be easily understood if the frequencies above 3,000 cycles are eliminated, they sound very unnatural, and again tire the ear, causing irritation. The higher frequencies are really necessary to give clearness, definition, and depth to the sounds, and since they consist mostly of the harmonics, they are the means of recognizing different instruments which produce the same notes, and different voices (see Article 6).

It is evident from a consideration of these facts, that the average ear is a rather poor measuring instrument and should not be trusted too much in judging either frequency or intensity of sound outputs. It is also evident that the sound output from an audio amplifier and loud speaker combination can be quite far from an exact reproduction of the original sound and still appear satisfactory to the ear. At medium frequencies, a change in frequency of about 0.3 per cent can be detected, at low frequencies a change of about 1 per cent is necessary for detection by the ear. Another phenomenon of hearing which enters into the sensation of sound, is called *masking*. Lower pitched tones in a sound deafen the hearer to the higher tones, and this masking effect becomes marked when the loudness of the low tones is great. Masking of the higher notes makes the combined sound appear to be lower in pitch. For true reproduction then, the sounds should be reproduced with about the same loudness as the original sounds in the broadcast studio. Intense high-frequency notes do not appear to mask low-frequency notes to any degree.

422. Compensating for side-band suppression: In this discussion it has been assumed that the audio amplifier is to follow an r-f amplifier and detector in which no side-band frequencies are suppressed (see Article 358) and in which no other distortion takes place. If this is not the case, the problem becomes further complicated, as the amount of side-band suppression is rarely known. If it is known, it can be corrected in the audio-frequency amplifier system by increasing the amplification of the high frequencies which have been suppressed in the r-f amplifier. This is beyond the scope of the home constructor but is feasible for manufacturers who sell sets complete with built-in loud speakers.

It must be remembered that the cutting off of some of the lower frequencies does not prevent the listener from hearing these notes, for the second (and possibly the third) harmonics of these are amplified and passed on. The ear partly adds the fundamental pitch of a note, of which only the harmonics are being produced, so that these notes are heard, although the "quality," "timbre," or "tone color" of the tone is changed. If it were not for this fact, some of our older sets and speakers would sound terrible, as they do not reproduce any of the fundamentals below 200 or 300 cycles. Timbre is probably more important in music than in speech, as it is one of the things that distinguishes the tones of the various instruments. In general, the fundamental and first two or three overtones are necessary in order to distinguish clearly the tones of the various instruments.

It can be seen that an a-f amplifying and reproducing system may fall considerably short of the ideal without giving really objectionable reception, due to the peculiarities of hearing of the average person. A trained ear could possibly detect the elimination of frequencies above 8,000 cycles per second from the ordinary run of music, but the average individual would have difficulty in detecting the elimination of frequencies above 6,000 or 7,000 cycles, unless he paid particularly close attention to each of the instruments in an orchestral selection. The factor which really guides the design, is how good the system will be when apparatus which is not prohibitive in cost is used under practical working conditions.

423. The transmission unit—decibel: Before proceeding with the study of audio amplifiers, it is necessary that we learn something of the common methods used to express and compare their operating characteristics. Then we will be prepared to pass judgment on the worth of any amplifier system.

It has been determined experimentally that the response of the human ear is such that the impression it gives of *loudness* of a single note is not linearly proportional to the sound energy acting upon it but is *approximately* proportional to the *logarithm* of sound energy. For example, a full orchestra playing a passage of music at its full volume creates sound energy about 1,000,000 times as great as when it plays this same passage at its softest volume. However, to the average normal ear the loud passage does not sound 1,000,000 times as loud as the soft passage. It sounds only about *60* times as loud. The *energy* ratio in this case is 1,000,000 to 1. The *loudness* ratio (as perceived by the ear) produced by it is only about 60 to 1.

(This fortunate provision of nature is really a blessing in a way, for it protects our delicate ear mechanism against injury from sound waves of great energy.)

It is evident then, that in any electrical system having to do with the transmission, amplification, or reduction, of electrical energy which is finally to be changed into sound energy it is convenient to have a unit of transmission efficiency that bears some close relationship to the logarithmic loudness response characteristic of the average human ear and also that can be treated by the ordinary processes of addition and subtraction in order to obtain the total *gains* or *losses* in a circuit. In order to do this it is necessary that the unit be an exponential one, and it was for this reason that the *decibel* was chosen as the unit of transmission efficiency.

In communication work *the common logarithm* of the ratio of the power P_2 which exists in the termination or receiver when the device or circuit under consideration is inserted, to the power P_1 which exists in the*

termination or receiver when the device or circuit is removed is a measure of the transmission "loss" or "gain", in "bels" which the device or circuit introduces. That is, bels$=\log_{10} \dfrac{P_2}{P_1}$.

The bel was named in honor of Alexander Bell the inventor of the telephone. Since for the ordinary power ratios encountered in practice the bel is too large a unit for convenient expression, the *decibel*† (one-tenth of a bel) is the unit more commonly used. Therefore, since 1 decibel$=0.1$ bel and, conversely, 1 bel equals 10 decibels, the number of *decibels* difference in level between P_2 watts and P_1 watts is

$$\text{Decibels} = 10 \log_{10} \frac{P_2}{P_1}$$

(In telephone work) the decibel (abbreviated DB, or db) has also been called the *transmission unit* (abbreviated TU).

The two power values P_2 and P_1 in the equation for decibels must both be expressed in the same unit (kilowatts, watts, milliwatts, microwatts, etc.). If the ratio of the *output* power (P_2) is greater than the *input* power (P_1), there is a "positive" *gain*. If the output power (P_2) is less than the input power (P_1) there is *loss* (indicated by a *negative* sign for the logarithm value).

It happens that only a trained musical person could notice any difference in loudness produced by a 1-DB change in the sound energy intensity of a single note. Changes of less than 1DB cannot be noticed by the human ear. In fact, to most persons, even a 2DB change is only slightly noticeable. Thus, an increase from 3 watts to 4.75 watts is only a slightly audible increment, since it is an increase of 2DB in sound energy.

*The common logarithm of a number is the power to which 10 must be raised to equal the number. Thus, log $10=1$; log $100=2$ (because $10^2=100$); log $1000=3$ (because $10^3=1000$). Similarly, log $45=1.653$ because $10^{1.653}=45$. This common system of logarithms uses 10 for the base. The values of the logarithms of numbers may be obtained from tables published in books on Algebra, Trigonometry, etc., but this is rather tedious work. The chart of Fig. 304 makes the work of solving decibel equations simple, for no logarithms need be looked up. First locate the point corresponding to the given *loss* (or *gain*) ratio on the left, or right hand, vertical scale respectively. From this point project across horizontally to the heavy diagonal "loss (or "gain") line. Then project downward from this point of intersection to the decibel scale at the bottom. If the given ratio involves *power* values, the decibel value is read on the upper horizontal scale marked "power Scale." If the given ratio involves *currents* or *voltages*, the decibel value is read on the lower horizontal scale marked "voltage or current scale."

†It must always be remembered that the *loudness* response of the human ear for the wide range of frequencies in music is not *exactly* in accordance with the logarithmic unit of transmission efficiency (the decibel), for the ear is not equally responsive to all sound frequencies (see Art. 420 and Fig. 303). Hence confusion between the Decibel which is not a loudness unit but a unit of *change of power*, and the Phon which is a true *loudness* unit should be avoided If the ear were equally responsive to all frequencies, the Phon and the decibel would be identical.

It should be remembered that the basis of the decibel as a unit of loss or gain is founded on *power* ratios. However, voltage or current ratios can also be used. In such cases since $P=I^2 \times R$ or E^2/R, substituting these values for P in the equation for decibels, we obtain:

$$\text{decibels} = 10 \log_{10} \frac{(I_2)^2 R_2}{(I_1)^2 R_1} = 20 \log_{10} \frac{I_2 \sqrt{R_2}}{I_1 \sqrt{R_1}}$$

$$\text{likewise, decibels} = 20 \log_{10} \frac{E_2/\sqrt{R_2}}{E_1/\sqrt{R_1}}$$

(The factor 20 appears in the above expression since the right hand expression appeared as a number "squared." Since the logarithm of the power of a number is equal to the logarithm of the number multiplied by the exponent of the power, this gives 10×2, or 20, in front of the logarithm expression.)

If the resistances into which the two currents I_2 and I_1 flow are equal, or across which the two voltages E_2 and E_1 appear are equal, then R_2 and R_2 cancel, and these expressions reduce to the simple forms:

$$DB = 20 \log_{10} \frac{E_2}{E_1}, \qquad \text{and } DB = 20 \log_{10} \frac{I_2}{I_1}$$

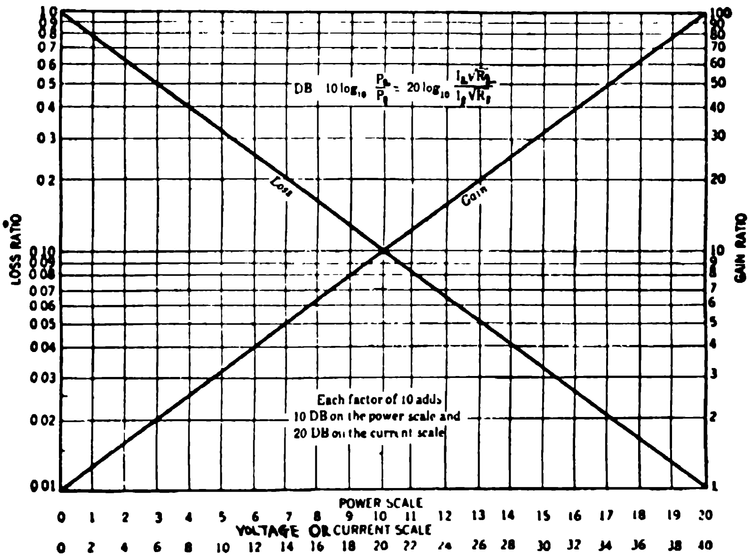


Fig. 304—Chart for quickly obtaining decibel values for various gain or loss ratios of power, current, or voltage.

The same holds true in the case of a-c circuits, provided that the impedances Z_2 and Z_1 across which E_2 and E_1 are measured are equal. When the impedances are not equal, the gain in decibels is

$$DB = 20 \log_{10} \frac{E_2}{E_1} + 10 \log_{10} \frac{Z_1}{Z_1} + 10 \log_{10} \frac{k_2}{k_1}$$

$$\text{also, } DB = 20 \log_{10} \frac{I_2}{I_1} + 10 \log_{10} \frac{Z_2}{Z_1} + 10 \log_{10} \frac{k_2}{k_1}$$

where, Z_1 and Z_2 are the corresponding impedances, and k_1 and k_2 are the corresponding

power factors of these impedances.

To illustrate the use of the decibel formula for calculating *gains* and *losses* in circuits involving **a change of power at one point**, suppose that an amplifier driving a loudspeaker is delivering 1 watt to it and that subsequently this is *increased* to 2 watts, i.e., the power is doubled. The *gain* in decibels is then

$$\text{gain} = 10 \log_{10} \frac{2}{1} = 10 \log_{10} 2 = 10 \times 0.301 = +3.01 \text{ DB}$$

In a similar manner suppose the original power was 2 watts and it was then decreased to 1 watt. This represents a *loss* in power, and the ratio is 1 to 2. The *loss* is therefore

$$\text{loss} = 10 \log_{10} \frac{1}{2} = 10 \log_{10} 0.5 = 10 \times \bar{1}.699 = -3.01 \text{ DB}$$

To illustrate the use of the decibel formula to calculate a **difference in power existing between two points**, consider an amplifier having an input of 0.002 watts into 500 ohms and an output of 0.2 watts. The power *gain* due to the amplifier is then

$$\text{gain} = 10 \log_{10} \frac{0.2}{0.002} = 10 \log_{10} 100 = 10 \times 2 = +20 \text{ DB}$$

This amplifier may therefore be described as having a *gain* of 20 DB (this neglects any consideration of the input or output impedance)

Reference Levels: What has been said thus far refers to the application of the "decibel" to increases or decreases in power.

The next important use of the decibel is for "power level" considerations, that is, for expressing the power existing at any point in a circuit as so many DB *above*, or *below*, a standard amount of power. Since decibels refer to *ratios*, they may only be used in this way (as a measure of *absolute magnitude*) when referred to a definite *reference level*. The very term "power level" implies that we have established a standard "zero reference level" by which to gauge all others.

Unfortunately, there is no one power reference level standard which has been universally adopted, and until such standardization has been accomplished it is always important to clearly specify what reference level is being used. Several levels have been in common use. Thus, 6 milliwatts (O DB=0.006 watts) is widely used in sound picture and public address system work; RCA rates its equipment on a 12.5 milliwatt "zero level" basis; the U. S. Navy has used 1 milliwatt as the zero level in its specifications, etc.

If 0.006 watts is considered as the zero reference level, then since the number of DB equals $10 \log \frac{P_2}{P_1}$

$$\text{Power level}_{(DB)} = 10 \log_{10} \frac{\text{power (watts)}}{0.006}$$

For example, if an amplifier delivers 0.06 watts to its output circuit, its power output level is

$$\text{DB} = 10 \log_{10} \frac{0.06}{0.006} = 10 \log_{10} 10 = +10$$

This could be written: Power level=10DB/0.006 watts

to indicate definitely that the amplifier under consideration delivers a power level which is 10DB above the arbitrary reference level of 0.006 watts.

Overall Gain or Loss: Because of the logarithmic character of the decibel, successive gains and losses expressed in db are added algebraically (when two numbers are to be multiplied, their logarithms are added), provided they are all expressed with reference to the same reference power level. For instance, suppose we have a system

containing successively an amplifier giving a positive *gain* of 40 db, a line having a negative gain (*loss*) of 5 db, an impedance-matching network giving a negative gain (*loss*) of 30 db, and ending up with an amplifier contributing a positive *gain* of 10 db—(all gains and losses referred to the same reference power level). The overall *gain* of the system, from the input of the first amplifier to the output of the terminating amplifier, would be +40db—5db—30db+10db=+15db. This feature itself contributes considerably to the simplification of power level calculations where there are a number of pieces of equipment between the input and output terminals of a system. Once the gain (or *loss*) for each piece of equipment is known (providing the couplings have proper characteristics) it is necessary only to perform a simple algebraic addition to determine the overall gain (or *loss*) for the entire system.

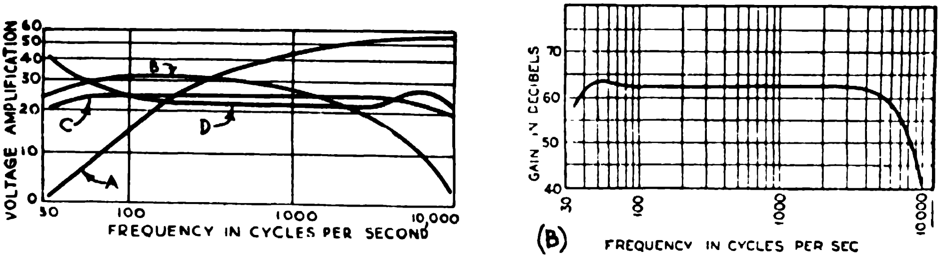


Fig 305—Left Audio amplifier response curves plotted with "voltage amplification" along the vertical scale
Right Audio amplifier response curves plotted with "gain in decibels" along the vertical scale

424. Frequency-response curves: One important thing to know about an audio amplifier, is how much it amplifies equal input voltages of different frequencies in the audio range. This data is obtained by applying equal signal voltages of the various known frequencies to the input, and measuring the output voltage in each case with a vacuum tube voltmeter or other suitable device. The results of such a test may be plotted in the form of a graph, with frequency along the horizontal scale and voltage amplification along the vertical scale as shown in Fig. 305. This is called the *frequency-response* curve of the amplifier.

The frequency-response curves should *not* be plotted with the frequency laid off uniformly along the horizontal axis. Since the ear hears logarithmically, the response curves are usually plotted so that distances along the horizontal frequency scale are made proportional to the logarithm of the frequency. The vertical scale is drawn proportional to the logarithm of the voltage amplification, as shown in the curves at the left of Fig. 305. In some curves the gain in decibels is plotted along the vertical scale as shown in the curve at (B). In this case, equal gains in decibels are represented by equal divisions on the scale. This is all due to the fact that we hear logarithmically. The difference in pitch between two sounds as heard by the human ear, corresponds to the logarithm of the ratio of their frequencies. Similarly, the ear's response to differences in loudness are nearly proportional to the logarithm of the difference in pressure. Therefore, the audio-frequency response curves should be plotted this way in order to show the variations in their relative intensities just as they would actually affect the ear.

It is essential that the frequency-response curve of any audio coupling unit should show the performance of the unit when in actual use, that is, with its associated vacuum tubes and under operating conditions. A curve of a transformer, impedance

coupling unit, resistance coupling unit, etc., when used with the testing device only, and not in actual practice with the correct vacuum tubes and plate and grid voltages, is useless, since the performance will be different in actual practice, due to added tube capacities, etc. The plate resistance of the tube (which depends among other things, on the plate voltage and filament current) will affect the operation of the coupling unit. If this is a transformer, the load applied will produce marked changes. Considering all these factors, frequency response curves are without real value unless made under actual operating conditions.

425. Coupling methods: In most a-f amplifiers, the greater portion of the amplification is produced by vacuum tubes, and the usual problem of coupling each two successive tubes together so that plate current changes in one will cause corresponding grid potential changes on the next, arises. Fig. 306 shows a simplified diagram of a two stage amp-

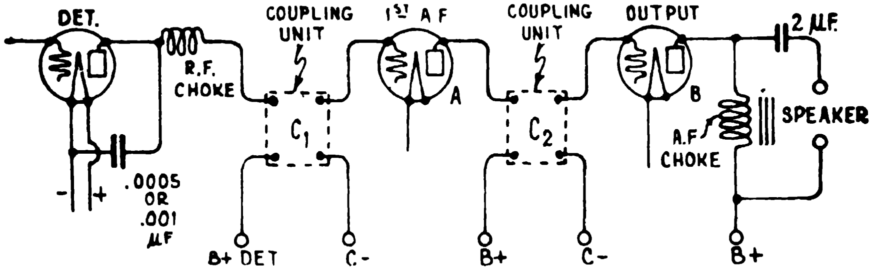


Fig. 306—How the coupling units are connected between the successive amplifier tubes of an a-f amplifier These transform the plate current changes existing in one tube, to grid voltage changes applied to the following tube

lifier in which amplification is secured by first-stage tube A and output-tube B. The coupling units C1 and C2 serve to couple the grid and plate circuits of successive tubes together. The output or varying plate current of one tube must be made to flow through an impedance, (see Art. 336), producing a varying voltage drop which is applied to the grid circuit of the next tube. This impedance, or coupling unit between, may take the form of an inductance or a resistance. This leads to three popular main forms of coupling for a-f amplifiers.

(1) Transformer Coupling.
(2) Resistance Coupling.
(3) Impedance Coupling.

Each system has its own peculiar limitations and advantages. They can all be made to work surprisingly well under certain conditions. The operation of each will be studied separately.

426. Transformer-coupled a-f amplifier: Fig. 307 shows a circuit diagram of a conventional two-stage transformer-coupled a-f amplifier. In Fig. 308 a single stage of this amplifier has been drawn separately for purposes of analysis of the actions taking place. We will study the design and construction of the coupling transformers in detail presently. For our purpose at the present time, suffice it to say that the transformer T, is constructed with a primary and secondary winding on a steel core,

usually with the secondary having more turns than the primary so that a step-up in the voltage occurs in the transformer itself. One stage of amplification comprises tube A and transformer T. Varying signal voltages applied to the grid circuit of tube A, cause corresponding varying plate current changes. This varying plate current flows through the primary winding. If the current is increasing, the e. m. f. induced in the secondary will be in a certain direction; if the current through the primary is decreasing, the induced e. m. f. in the secondary will be in the reverse direction. Thus, with a pulsating or varying direct current through the primary winding, an alternating e. m. f. is induced in the secondary. No voltage, however, is induced in the secondary when the current through the primary is steady. The output voltage of one stage can be fed to the input of another stage, etc., so that the signal may be amplified again and again, and built up to the desired strength.

Now, referring to (A) of Fig. 308, we can see that the primary winding of the transformer is connected in the plate circuit of the previous tube and the secondary is connected across the grid input circuit of the following tube. Let E_1 be the a-f signal voltage applied to the input of the stage. This is equivalent to an a-f voltage of μE_1 (μ is the amplification constant of the tube) introduced in the plate circuit of the first tube A, tending to cause the a-f component of the plate current to flow. The plate-to-filament path in the tube acts like a variable resistance equal in value to the plate impedance of the tube. The primary of the audio transformer, consisting of thousands of turns of wire wound on an iron core, has appreciable inductance, so that it presents an impedance to the varying a-f plate current. These facts can be used to draw the simplified equivalent circuit diagram (B), where μE_1 is a source of a-f voltage tending to send current around the circuit through the plate resistance

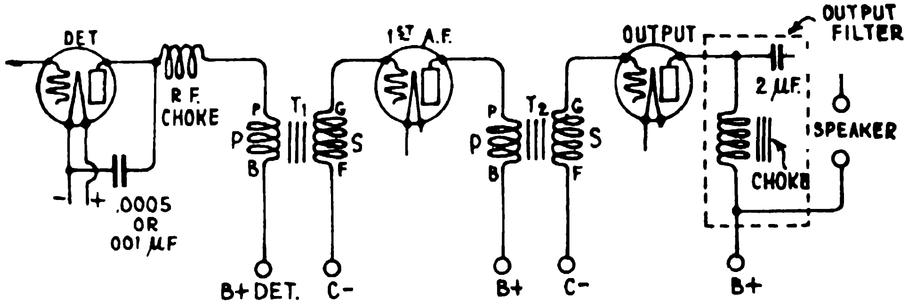


Fig 307—Transformer coupling units between successive tubes of an a-f amplifier

R_p, and the transformer primary impedance Z. This current, flowing through R_p and Z, produces a fall of potential across each, the sum of the two being equal to μE_1. The varying voltage or fall of potential appearing across the primary of the transformer is stepped up by an amount equal to the turns ratio. This secondary voltage E_2 is impressed on the

grid circuit of the following tube. As the vacuum tube is a voltage-operated device (changes in grid *voltage* producing changes in plate current) we are interested in getting as large a voltage E_2 across the input of the second tube as possible. This means that as large a voltage drop as possible must be developed across the primary (see article 337). Therefore, its impedance must be made high compared to the plate impedance of the tube. If N is the turns-ratio of the transformer, the amplification of a complete transformer-coupled *stage* for each frequency then is:

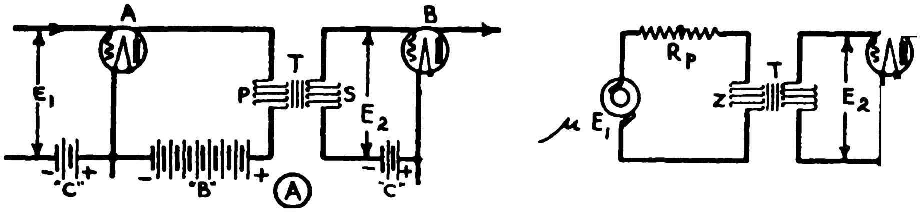


Fig. 308—The typical transformer-coupled a-f amplifier stage at (A) may be considered as shown at (B) for purposes of analysis of the actions

$$\text{Amplification} = \mu \frac{Z}{Z+R_p} N.$$

If the transformer primary impedance Z is very high compared to R_p, so that the relation $\frac{Z}{Z+R_p}$ is nearly equal to 1, the amplification of the stage can be reasonably assumed to be equal to the amplification factor of the tube times the turns-ratio of the transformer. Of course this is true only when a transformer having a high-impedance primary is used, and as we shall see, this value is not exactly constant at all frequencies. Actually, if the transformer primary impedance is about 3 times the plate impedance of the tube, an amplification equal to 75 per cent of the mu of the tube multiplied by the turns-ratio of the transformer is obtained. It should be remembered that in a transformer-coupled a-f amplifier the transformers contribute to the step-up in voltage. For this reason, if the same type of tubes are employed, a transformer-coupled a-f amplifier requires less stages for a given total amplification than either the resistance or the impedance coupled types do. This is one of its advantages.

427. Design of the a-f transformer: An audio transformer consists of a primary and secondary winding placed on a laminated magnetic core (usually shell-type as shown in Fig. 72), of silicon-steel, nickel-steel, or other special alloys. As shown in Fig. 309, the primary is wound inside around the center core leg and insulated from the core. Around this, and insulated from it is the secondary winding.

A steel core can be used in a-f transformers because since the frequencies of the currents in them will never be above 5,000 to 8,000 cycles or so, the losses due to

the eddy currents and hysteresis can be kept small by proper design. It will be remembered that ordinary steel cores could not be used satisfactorily in r-f transformers on account of the excessive losses at the high radio frequencies.

The secondary usually has more turns than the primary, in order to step-up the voltage. The usual turns-ratios employed are between 2 to 1, and 4 to 1. However, it is evident that not only the turns-ratio but also the impedance of the primary winding is important in determining the total voltage amplification of each stage. The turns-ratio determines how much the signal-voltage variations applied to the primary will be stepped up in the transformer, but the primary impedance determines just how strong these signal-voltage variations appearing across the primary, will be.

The windings consist of many thousands of turns of about No. 40 or 44 enameled copper wire. Small wire is used so that a large number of turns can be wound in a small space. No. 40 wire will safely carry about 1.85 amperes. The cores are laminated to reduce eddy current effects due to the constantly changing magnetic field. The shell type or "closed" core shown in Fig. 309 is used most, because of the small amount of magnetic leakage between the primary and secondary. The primary is usually placed inside of the secondary, and if both coils are wound in the same direction the connecting leads are usually taken off in the order shown. The inside end of the primary (P) goes to the plate of the vacuum tube, the outside end (B+) goes to the B+ terminal of the "B" voltage supply. The inside end (F–) of the secondary goes to the negative terminal of the grid-bias voltage source, and the outside end (G) goes to the grid. This keeps the grid and plate terminals as far apart as possible, thus lowering the effective capacity across the coils. Fig. 310 shows a typical high grade transformer removed from its soft iron protective case. The markings which appear on the terminals a-f transformers are such as to assist in connecting them up. Thus the terminal of the primary which goes to the *plate* of the tube is marked "P". The other end, which goes to the B+ source is marked "B+". The end of the secondary which goes to the *grid* of the following tube is marked "G", and the end which goes to the negative terminal of the grid-bias source is marked F–. The connections of the transformer in the actual circuit are shown in Fig. 307.

Since the primary of an a-f transformer consists of a great many turns of wire wound on an iron core, it has inductance, and presents an

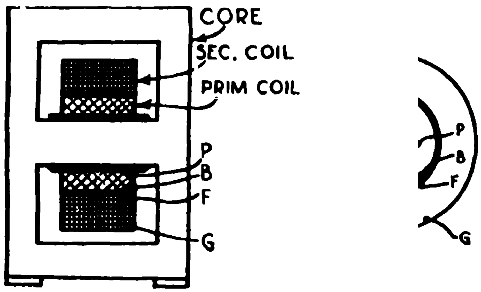


Fig 309—Cross-section and side view, of an a-f transformer, showing the relative positions of the primary, secondary, core, and terminals. The terminals of the windings are arranged so that the minimum capacitance exists between the P and G terminals.

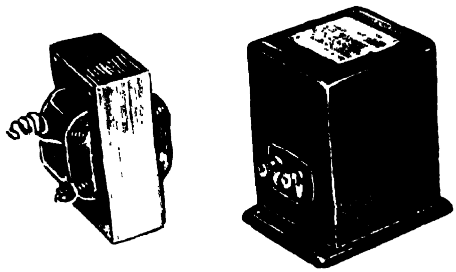


Photo Courtesy Pilot Radio & Tube Corp.

Fig. 310—A typical a-f transformer and its metal enclosing case. Notice the substantial core and windings. This transformer contains about 16,000 turns of No. 40 enameled wire, which, if stretched out straight, would be nearly a mile in length.

impedance or opposition to any variation of the plate current flowing through it. Its impedance varies with the frequency of the plate current

variations, being much greater when the higher frequency audio signal voltages are being received than when those of lower frequency are coming through. The signal voltage E_1 impressed on the tube may be of any frequency between 40 and about 5000 cycles, depending on the range of frequencies concerned in the reproduction of the speech and music being received. Practically, the result is that at the low frequencies at which the transformer impedance is low, very little of the total applied plate circuit voltage is effective across the transformer; most of it is across the tube. At the higher frequencies a greater proportion of it is applied to the transformer, because the transformer primary impedance is higher. As a result of this, the low notes do not receive as much amplification as

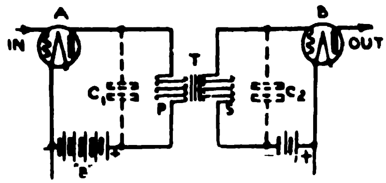


Fig 311—The distributed capacity of the primary and secondary windings on an a-f transformer may be represented by the condensers C, and C2 across these windings

do the moderate and high frequencies, resulting in distortion of the program. Actually, the high frequencies are reduced somewhat by the decrease of amplification due to the distributed capacity of the windings.

The frequency response of an a-f transformer having a characteristic like this is shown by curve A in Fig. 305. In order to keep the amplification up at the low frequencies, the primary impedance must be designed to be large at these frequencies, compared with the plate impedance of the tube. Since the impedance increases with the frequency, there is no difficulty in obtaining the necessary high impedance at the upper audio frequencies. The impedance at low frequencies depends upon the inductance. The larger the inductance the greater the impedance. To get a large inductance a large number of turns of wire are required on the primary coil, and a core material of high permeability must be used. This makes the transformer more expensive of course.

If the voltage step-up property of the transformer is to be made available, the secondary must have more turns than the primary (in a 3 to 1 transformer the secondary has 3 times as many turns as the primary). Let us assume a 3 to 1 transformer. If the primary contains enough turns to have the proper impedance necessary to match that of the tube, the secondary will have 3 times as many turns and be very large and expensive. Also, the large number of turns of wire on both the primary and secondary coils will have a large distributed capacity. These will act as shunt condensers C_1 and C_2, across the coils, as shown in Fig. 311. Since the reactance of a condenser decreases as the frequency is increased, the effect of C_1 is to shunt the high-frequency plate current variations

away from the primary of the transformer. One effect of this is to partially reduce the high-note response, since these shunted current variations do not produce any varying magnetic field or secondary voltage in the transformer. Condenser C_2 also has the effect of putting a load on the secondary coil, since currents flow back and forth in the circuit consisting of this capacity and the winding. The magnetic fields set up by these currents as they flow back and forth through the winding, oppose the magnetic field due to the primary, and so reduce the primary inductance, and the voltage transferred to tube B. The result is that the high distributed capacity in either of the windings cuts down the amplification of the high frequencies, and since the high-frequency notes are therefore not reproduced, distortion results. Curve B (Fig. 305) shows the frequency response of a stage of a-f amplification using a transformer of this kind. Notice that the response at the low notes has been improved greatly, at the expense of the high notes. (One manufacturer reduces the distributed capacity by winding the coils in helical fashion.) The size of the secondary coil could be kept down by making a 1 to 1 transformer, but then the amplification would be reduced.

It can be seen that a compromise must be made between primary inductance, turn-ratio, and cost. The turn-ratios of modern high grade transformers vary from about 2 to 1 to 4 to 1, 3½ to 1 being a common value. The primary inductance is made large enough to reproduce the low notes well, without serious decrease in high-frequency response due to distributed capacity. Curve C shows the frequency response of an a-f amplifier stage using a high-grade transformer. Notice the compromise between curves A and B. An idea of the characteristics of this transformer can be obtained from its specifications: turn-ratio 3 to 1, primary inductance 100 henrys, primary resistance 3,700 ohms, primary impedance 19,000 ohms at 32 cycles, 626,000 ohms at 1000 cycles under operating conditions. Secondary inductance 900 henrys, secondary resistance 10,000 ohms. Referring to Fig. 214, we find that the a-c plate resistance of a '27 type tube operated as an amplifier is 9,000 ohms. Therefore, the impedance of this transformer is about twice as great as that of the tube at 32 cycles, so that about 0.7 of the mu of the tube would be obtained, (mu$=$9) at the lower frequencies. The amplification *per stage*, at this frequency would be $.7 \times 9 \times 3 = 19$ approximately.

428. Transformer ratio: The effect of the transformer ratio on the total amplification of an a-f stage (tube and transformer) is usually very misleading. We know from the foregoing discussion that a high-ratio transformer is more desirable from the standpoint of transformer voltage step-up than one of lower ratio. But the advantage gained by the use of the higher ratio transformer depends upon how the higher ratio is obtained. Some manufacturers put out a line of transformers of various ratios in which the number of secondary turns is the same for all transformers. Various ratios are obtained by changing the number of primary turns. Thus, their 1 to 1 transformer has equal primary and secondary turns. Their 3 to 1 transformer has the same number of secondary turns but only one third as many primary turns. Obviously the 3 to 1 transformer has a higher step-up voltage in itself, but the impedance of its primary is so low compared to the plate impedance of the tube that the amplification of the low-frequency signal voltages is greatly reduced and the low notes are slighted. The amount of amplification lost

through this poor match is usually greater than the amount gained in the transformer by the higher ratio. With such transformers, it is sometimes found that an amplifier using 2 to 1 transformers produces more amplification and better quality of reproduction (due to the higher primary impedance) than one using 5 or 6 to 1 transformers of the same make.

A transformer following a detector tube should necessarily have a high impedance primary if high amplification is to be obtained, because a vacuum tube has a high plate resistance when connected as a detector. If transformers of different ratios are to be used in a two stage amplifier, the transformer having the higher primary impedance should *always* follow the detector tube in order to match its plate resistance better—no matter what the turns-ratio is.

429. Large size transformers and core saturation: The primary of each audio transformer has flowing in it, the direct plate current of the preceeding tube, varying at audio frequency. It is only the *variations* in the current that are effective in producing voltages in the secondary, the steady direct component of the plate current (see (C) of Fig. 275) produces absolutely no voltage in the secondary. It merely produces magnetic lines of force which tend to magnetically saturate the core of the transformer and cause distortion due to the decreased inductance of the coils. The subject of transformer and choke-coil core saturation was studied in Article 123. If the plate current is large enough so that the increases of the plate current when the grid becomes *less* negative, cause the iron to operate over the "knee" of the magnetization curve, then the flux change and the secondary induced e. m. f. due to the positive half of each signal impulse will be less than those due to each negative half, and consequently, distortion of the wave-form of the signal voltage will result. The result will be a reduction of the upper half of each plate current ripple. Also the inductance of the primary is decreased due to the decreased flux changes, and less voltage therefore appears across the secondary. Since the voltage appearing across the secondary coil is proportional at any instant to the change in magnetism in the core at that instant, it is evident that the secondary voltage wave-form will be distorted by the non-linear characteristics of the iron. This is sometimes called ***hysteretic distortion***, because it is caused by the hysteresis in iron (Art. 99). Hysteretic distortion, which may cause serious distortion of the wave-form of the signal, is not shown by the ordinary frequency-response curves of Fig. 305. Thus, while an audio amplifier may have a perfect frequency-response characteristic, excessive hysteretic distortion may make it a very poor amplifier when operated for the amplification of speech and musical frequency voltages.

Saturation can be avoided by the use of rather large amounts of steel in the cores. The increased amount of copper and steel used in modern high-grade audio transformers is the result of a study of these factors. Of course, the cost has also increased. Some manufacturers use special nickel-steel alloys of very high permeability for the trânsformer cores, in order to obtain a high primary inductance. However, the danger of core saturation is greater with these materials on account of the

increased magnetic field produced by a given steady plate current and the parallel-plate feed circuit is usually employed with them to avoid this. The steady flux is decreased by some manufacturers by inserting a small air-gap in the magnetic circuit. This also decreases the primary inductance slightly, but helps solve the problem of saturation. A solution to this problem is the use of the parallel or shunt feed plate supply, connection described in Article 356.

430. Parallel-feed plate supply: The trouble arising from the effects of the steady direct plate current flowing through the primary of the audio transformer can be eliminated by keeping this current out of the winding and allowing only the varying a-f signal component of the current to flow through. One way of doing this is by connecting a blocking condenser C in series with the transformer primary and supplying the steady plate potential to the plate of the tube either through a resistance

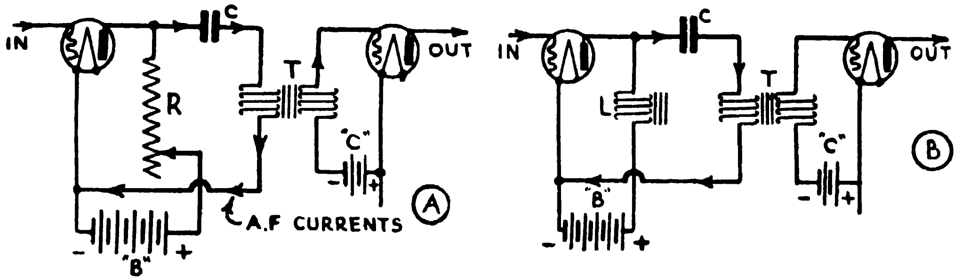


Fig. 312—Two arrangements for parallel feed of the plate voltage supply

R, as in (A) of Fig. 312, or an audio choke coil L, as in (B). Condenser C blocks the passage of steady direct current, but is made of large enough capacity (2 to 4 mfd.) so its impedance to the passage of the a-f currents flowing through the primary winding of the transformer is very low. The resistance R (about 30,000 ohms), or the choke coil L (100 henries), block the a-f currents (since they offer a high impedance to these currents), but allow the easy passage of the direct plate current. The path of the a-f currents is shown by the arrows. This system gives slightly lower amplification and increases the cost of the amplifier, but presents a means for eliminating the distortion caused by the direct plate current.

431. Clough system with resonated primary: An improvement in the parallel-feed method of transformer coupling, known as the Clough system, is shown in Fig. 313. The d-c component of the plate current flows through a resistance R of about 30,000 ohms (100,000 ohms for detector unit) which is connected as shown. The path of the a-c component is in the condenser C and lower portion (primary) of an auto-transformer through the grid-bias voltage supply, to the cathode circuit of tube B, and back to tube A, as shown by the arrows. Since the secondary of the auto-transformer includes the whole winding, there is a step-up in voltage, depending on the position of the tap. This ratio is usually made about 4.5 to 1. The system is so arranged that when a "B" potential of 180

volts is used, the voltage drop through the 100,000 ohm detector plate resistor is just sufficient to leave about 45 volts available for the detector plate, and the voltage drop through the 30,000 ohm plate resistor is just sufficient to leave about 135 volts available for the plate of the first audio tube. For tubes drawing different plate currents, different values of plate resistors can be used. This system gives a greater effective inductance for a given expenditure of copper and iron, due to the absence of the steady d-c current in the primary. Therefore, for a given low-frequency response, the primary and secondary turns can be made less in number than in an ordinary transformer connected in the ordinary way, thus reducing the distributed capacity and improving the high-frequency response. The

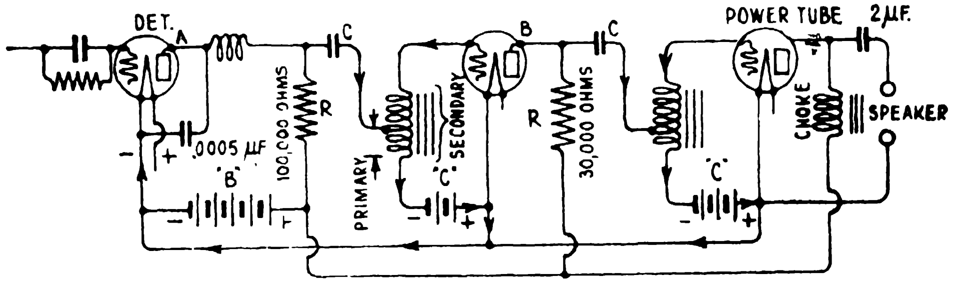


Fig 313—Typical 2 stage a-f amplifier arrangement using the Clough resonated primary system. This system can be used both in battery-operated and electrically-operated receivers.

low-frequency response can be altered at will by using condensers of various sizes for C.

As the reactance of C and that of the primary portion of the auto-transformer are opposite in sign, there is some frequency at which these reactances will be equal and they will be in resonance. At that resonant frequency, large voltages will exist across this condenser and primary. At this frequency there will be increased amplification, due to this large voltage developed across the primary by the resonance currents. It is possible to so select the coupling condenser C, that it resonates with the primary at a low frequency which normally is not amplified well, and so increase the gain at this frequency to any reasonable desired value, equal to, or greater than the gain of the stage at the other frequencies. It is even possible to resonate each stage at a different frequency to give almost any desired shape to the low-frequency part of the amplification curve of the amplifier. Curve D in Fig. 305 shows the response curve for a system of this kind in which the proper size of coupling condenser C was employed to produce resonance at about 30 cycles, to boost the low-frequency amplification. For instance, a transformer primary having an inductance of 125 henries will resonate at about 60 cycles with a condenser C, of about .05 mfd. The resistance, coupling condenser and auto-transformer are available in commercial units, enclosed in a case with proper terminals. Different units are used for the first and second stages.

As we shall see later, a very good form of adjustable low-frequency tone control can be included in this system by connecting a variable resistor in the resonant circuit. This system can also be employed with an ordinary audio-frequency transformer which has a separate primary and secondary winding.

432. Resistance coupling: The plate and grid circuits of succeeding audio amplifier tubes may also be connected together by means of a resistor in the plate circuit and one in the grid circuit,—with the grid isolated from the plate circuit insofar as the direct plate voltage is concerned, by a blocking condenser, as shown in the typical three-stage resistance-coupled amplifier of Fig. 314. The action in the first stage is typical of all the rest. The varying plate current I_p of the detector tube, flowing through plate resistor R_1 (about 100,000 ohms) produces a varying voltage drop across it equal to $I_p \times R_1$. Since the voltage of the plate battery is constant, this makes the *potential* of point A vary in exact accordance with the plate current variations. Now point A cannot be connected directly to the grid of the second tube, as a large positive grid bias due to the "B" battery would thereby be put on it. This would cause a grid current to flow and cause distortion, and also probably damage the tube due to the heavy plate current set up. It is removed by placing a blocking condenser C_1 between point A and the grid. If this condenser has good insulation, it presents practically infinite impedance to the continuous (or direct) voltage, but allows the alternating a-f signal voltages to act around its circuit. The presence of this blocking condenser necessitates that the grid be connected to the filament through a high resistance R_2 in order to provide a leakage path for the negative charges which would otherwise accumulate on the grid and block the operation of the tube. A negative grid bias potential for the grid is secured by connecting the lower terminal of R_2 to the negative terminal of the grid bias voltage source. This may be a "C" battery or a voltage-drop through a cathode resistor. The varying voltage across R_1 is thus impressed between the grid and cathode (through the grid return circuit) of the second tube. The following stages are similar, except that different resistor values may be used.

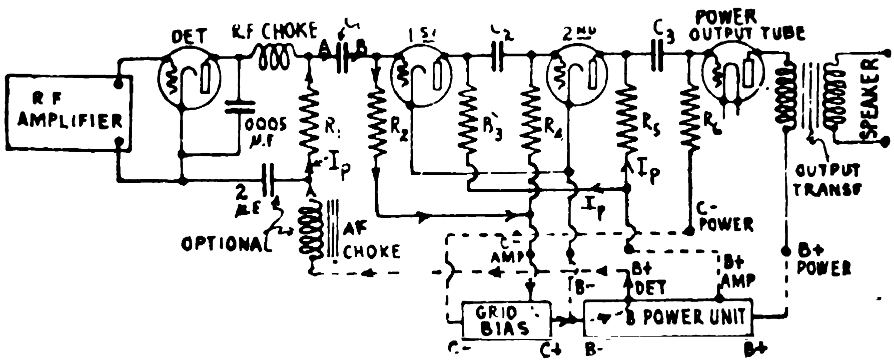


Fig. 314—Typical 3-stage resistance-coupled audio amplifier system

As there is no voltage step-up in the coupling resistors, all of the amplification is produced by the vacuum tubes. This makes it necessary to use more stages for a given amount of amplification than when transformer coupling is employed.

Theoretically, the plate resistors should be as large as possible, for the amplification per stage is proportional to the ratio of this resistance to the total plate circuit resistance. However, this resistance cannot be increased beyond certain practical limits, for the voltage effective at the plate of the tube is less than the "B" supply voltage by an amount equal to the $I_p R$ drop through the resistor. If the resistor is made too large, abnormally high "B" supply voltages are necessary in order to apply enough voltage to the plate of the tubes to operate them at the proper points on their characteristic curves to prevent distortion. Since the plate resistance of a vacuum tube operating as a detector is much higher than when acting as an amplifier, in general the plate resistor in the detector circuit should be of higher value than those used in the following amplifier stages, in order to effectively match the detector tube a-c plate resistance.

Each plate resistor is a pure resistance, but it has shunted across it, the plate-cathode capacitance of the tube (see (A) of Fig. 249). This tends to shunt the plate current variations at the high audio frequencies and so reduce the amplification at these frequencies. As the plate resistor is increased in value in order to obtain higher amplification, the plate-cathode capacity of the tube becomes more and more effective as a shunt across it and so tends to reduce the amplification at the higher frequencies. So a compromise must be made between "gain" and good high-frequency response.

The blocking condensers can also be a source of serious frequency-distortion due to the fact that their impedance varies with the frequency. Thus the impedance of a .01 mfd. condenser is about 530,000 ohms at 30 cycles and 5,300 ohms at 3,000 cycles. This varying impedance prevents the low-frequency currents from getting through as easily to the grid circuit, and being amplified as much as the high-frequency currents. Also, the blocking condenser and grid resistor form a circuit which requires a definite time for discharge of the negative charge accumulated on the grid. Unless this time constant is sufficiently short, the grid will usually block on strong signals resulting in a gurgling sound in the amplifier. This can be corrected in most cases by careful choice of the proper plate and "C" bias voltages. The amplification of a resistance-coupled amplifier can be made substantially uniform for all audio frequencies, provided the handling capacity is reduced somewhat. The amplifier is cheap to construct and the plate current drain is light, but the plate voltage supply must be high.

Resistance coupling is especially valuable in receivers using screen-grid tubes as detectors, or using power detectors. In these, the plate impedance is too high to permit of proper matching by the primary of a transformer of reasonable cost. By using a resistance-coupled audio stage following the detector, very good amplification and frequency-response may be obtained. The same is true when screen-grid tubes are to be used in the audio amplifier.

433. Sizes of resistors and condensers: The plate circuit resistors should preferably be at least three times the value of the a-c plate resistance of the tube. With this value, an amplification of .75 times the amplification factor of the tube is obtained for each stage. Larger values will increase this gain but the increased voltage drop in them necessitates the use of high "B" supply voltages, if normal values of effective plate voltage are to be applied to the tubes. Also, the plate-cathode capacity becomes more effective in reducing the high-frequency response. The resistors must be of high grade and of permanent resistance value, able to carry the plate current flowing through them without any undue heating or change in value. The actual values of these resistors used in practical amplifiers, will be shown in the diagrams of such amplifiers later when considering the complete battery-operated and a-c electric-operated receivers for sound-program and television reception.

The size of the coupling condenser and the grid leak largely affects the operation of the resistance-coupled amplifier and its stability and frequency-response. The condenser should be large to avoid loss of low-frequency voltage across it, and the leak resistor should be large to cause the voltage drop to be as large as possible. However, the condenser will take an appreciable time to discharge through a large leak when it is charged up by a strong signal. This will cause the amplifier to block by reducing the plate current to zero. The size of both is then limited to a value such as will allow the *strongest* signal to leak off in the time between the *highest* frequency to be received. This means that the size is a compromise, but it is best to keep the leak resistors as high as possible in order to reduce the loss of signal voltage. Since the last tubes in the amplifier handle more signal voltage than those up ahead, it is common to employ leaks of lower resistance value for the last tube to avoid "blocking". A .01 mfd. condenser is usually employed in receivers for broadcast reception and leaks from .05 to 5 megohms are used, depending on the conditions of signal strength, etc. Resistance-coupled audio amplifiers are used exclusively in television receivers. As their requirements for this service are somewhat specialized, they will be studied in detail in the chapter on television.

The blocking condensers should have high insulation resistance, for faulty insulation will allow some of the plate potential to leak through it to the grid of the next tube, causing distortion or complete inoperation.

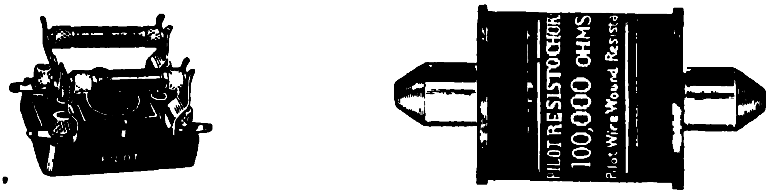


Fig 315—Left Resistance-coupling unit containing the plate and grid circuit resistors and the blocking condenser for a single amplifier stage
Right Wire-wound form of plate resistor with special end terminals to snap in place in the unit at the left.

Fig. 315 shows a commercial form of resistance-coupling unit consisting of a Bakelite base which contains the coupling condenser. The plate and grid resistors are of the cartridge type held in metal clips which also serve as connections. Several units of this kind can be wired up to form a complete amplifier. At the right is a wire-wound plate resistor unit designed especially to carry the plate current when high plate voltages are employed. All "B" and "C" circuits should be properly by-passed by condensers of at least 1 mfd. capacity to prevent interstage coupling in them.

434. Motorboating: When resistance or impedance-coupled amplifiers are operated with weak dry batteries or with socket-power operated "B" battery eliminators, trouble may arise due to coupling between the stages, because of the high internal resistance of these devices. This makes itself evident by the setting up of low-frequency audio-oscillations which sound like a motorboat engine, when reproduced by the loud speaker. This action is popularly known as *motorboating.*

Motorboating can sometimes be eliminated by reducing the internal coupling impedance by by-passing all coupling resistances in the "B" power supply with condensers of from 2 to 10 mfd. An audio-frequency

choke and large by-pass condenser in the detector plate lead, as shown in Fig. 314 usually helps by keeping the detector audio currents out of the plate supply unit. Coupling between the detector plate circuit and the plate circuits of the audio amplifier tubes is the cause of most motorboating. This coupling takes place due to the internal resistance or impedances in the "B" batteries or "B" eliminator, common to the various stages, (see Art. 377).

Thus in Fig. 316 let the resistance D-E-F-G represent the internal resistance of the "B" batteries or "B" eliminator operating the 3-stage resistance-coupled amplifier. The taps at E and F are for securing intermediate voltages. An alternating voltage impressed between points 1 and 2 is amplified by the audio amplifier and is then impressed on the grid of the last tube. This voltage will cause a pulsating audio fre-

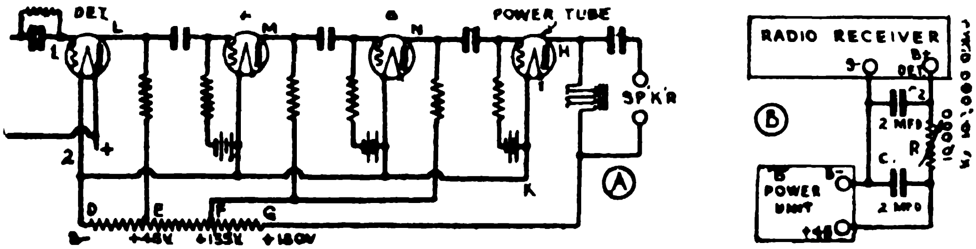


Fig 316—Left How interstage coupling may occur due to the impedance of the B supply unit in a multi-stage amplifier
Right How "motorboating" may be eliminated by means of a resistor and condensers connected between the B power unit and the radio receiver

quency current to flow in the plate circuit of the last tube. This current will flow in the path D-E-F-G-H-K. This varying audio-frequency current flowing through the resistances D-E and D-F will cause varying falls of potential across them. This will cause these varying audio-frequency voltages to be impressed back on the plate circuits D-E-L (detector-tube) D-E-F-M (tube A), and D-E-F-N (tube B). These audio-frequency voltages will depend on the currents and the impedances between the points DE and EF. This small voltage is again amplified and fed back, and if the phase relation of the fed-back voltages E_{ED} and E_{FD} is such that the original signal is increased by the feedback, the audio voltage will keep on increasing until the amplifier breaks into low-frequency oscillation and gives the characteristic motorboat sound.

If motorboating occurs in a transformer-coupled amplifier, it can usually be stopped by changing the phase angles of the voltages E_{ED} or E_{FD} by reversing the connections to the primary of one of the audio transformers

A simple cure for most cases of motorboating is also shown in the circuit of (B) in Fig. 316, which was developed by the E. T. Cunningham Co It eliminates coupling effects at the low frequencies. It can be built right in the receiver or can be added to any existing receiver installation by connecting the resistance R in series with the lead connecting the B+ detector terminal on the receiver to the B+ detector terminal on the power unit. Condensers C_1 and C_2 of 2 mfd. each are then connected as shown between the B— terminal and the two B+ terminals. It is preferable to locate the resistor R at a point close to the receiver, rather than at the power unit. The value of the resistance may be anywhere from 10,000 ohms to 100,000 ohms for best results, depending upon the characteristics of the receiver and power unit. A variable resistor is suitable. Since the resistor is in series with the B+ detector lead, a slightly higher plate voltage will have to be used to compensate for the IR voltage drop in the resistor.

435. Characteristics of resistance-coupled amplifiers: One of the advantages of the resistance-coupled audio amplifier is that it is compact and cheap to build and that, for low signal voltages at least, the amplification can be made very uniform over quite a wide frequency range. This characteristic makes it especially valuable in television work. Of course the gain per stage is quite low unless screen-grid tubes are employed (since all the amplification is due to the tubes alone). The "B" supply voltage must be increased above the normal value for the tube used, in order to compensate for the voltage drop in the plate resistor. The grid is always kept negative by the proper grid-bias voltage, as in the case of all other types of amplifiers.

436. Impedance-coupled a-f amplifiers: The impedance-coupled amplifier is similar to the resistance-coupled type just described, excepting that the plate resistors are replaced by inductance or impedance coils as shown in Fig. 317. Each coil consists of thousands of turns of wire wound on a laminated steel core A unit of this type is shown at the left of Fig. 318.

The resistance of these coils to direct current is comparatively low, but the opposition or impedance offered to currents of audio frequency is very much greater on account of the inductive effect. Thus the direct current component of the plate current is not opposed very much by the low d-c resistance of the choke coil windings, so comparatively low "B" supply voltages can be used The impedance offered to the a-c component however is very much higher, so that an effective match with the plate resistance of the tube is secured if chokes of sufficiently high inductance are used. The impedance varies with the frequency just as in the case of the transformer primary, so that large impedances must be used if the low frequencies are to be amplified. The effect of the blocking condenser and grid leak are the same as for the resistance coupled amplifier

As no voltage step-up is secured in the impedances, the amplification per stage is lower than that of transformer coupling—all the amplification

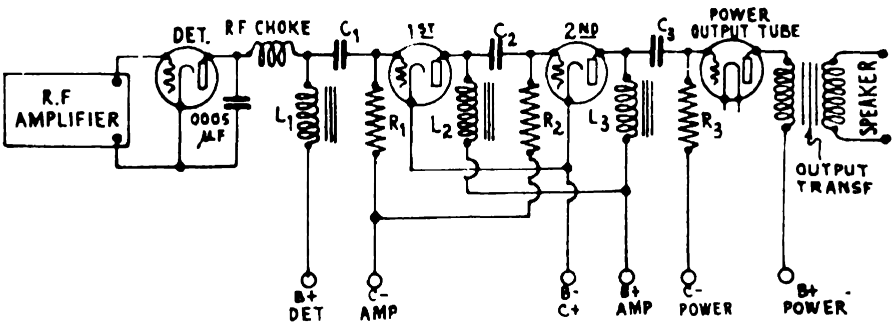


Fig 317—Typical 3-stage impedance-coupled amplifier arrangement

being due to the tubes themselves. For this reason, where two stages of transformer coupling would provide sufficient amplification, it is common to use at least three stages if either resistance or impedance coupling are employed. Any tendency toward motorboating can be removed by the

same method shown in Fig. 316. The same design considerations as regards size of blocking condenser, leak resistor, etc., apply for this amplifier as were mentioned in Article 433.

437. Autoformer impedance coupling: Some voltage step-up in the impedance coil can be obtained if it is connected up as an auto-transformer (Fig. 319), so that the plate current flows through only part of the winding (usually 2/3). The varying current induces a voltage in the remaining part of the winding, and the total voltage is applied to the grid circuit of the following tube. The circuit now possesses the voltage step-up features of a circuit employing a two-winding transformer, except that the blocking condenser and grid leak with their disadvantages are

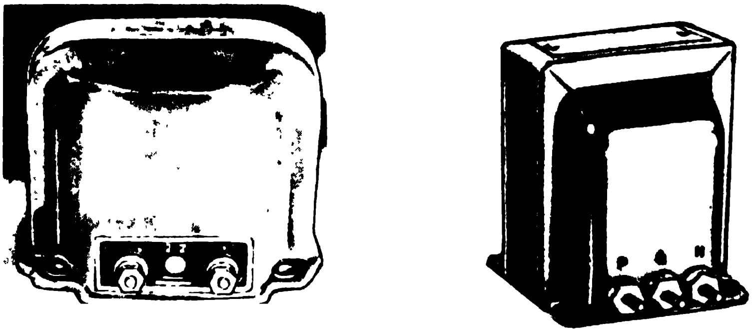


Fig 318—Left Typical iron-core impedance unit for use in impedance-coupled a-f amplifiers Right Typical auto-transformer for use in auto transformer coupling

still required. Auto-transformers can be built with much less wire and a smaller core to handle the same power and to have the same ratios as 2-winding transformers. By using well designed auto-transformers, proper blocking condensers and grid leaks, and a high mu tube, a two stage auto-transformer coupled amplifier may be built, having excellent frequency characteristics and about the same volume as the ordinary transformer coupled amplifier. It must be remembered that the position of the plate tap P is determined by the fact that the portion of the winding between P and B must have sufficient inductance to match the plate impedance of the tube at the low audio frequencies. A commercial autoformer unit manufactured especially for amplifiers of this type is shown at the right of Fig. 318. Notice the three terminals. Here again, the same design considerations as regards size of blocking condensers, leak resistors, etc., apply for this amplifier as were mentioned in Article 433.

438. Dual-impedance coupling: Another arrangement which has many of the advantages of the ordinary impedance-coupled amplifiers, with the additional advantage of giving higher voltage amplification, is known as *dual-impedance* coupling. As shown by a single stage of Fig. 320, two windings L_1 and L_2, having a 1 to 1 turns-ratio, are arranged

on a single core with a blocking condenser connected between them. Thus instead of the usual leak resistor we have an impedance-coil leak. An e. m. f. is introduced into the leak impedance by the mutual inductance between the plate coil and the impedance coil. At the same time they are arranged so the capacity between them is very small. The extra voltage

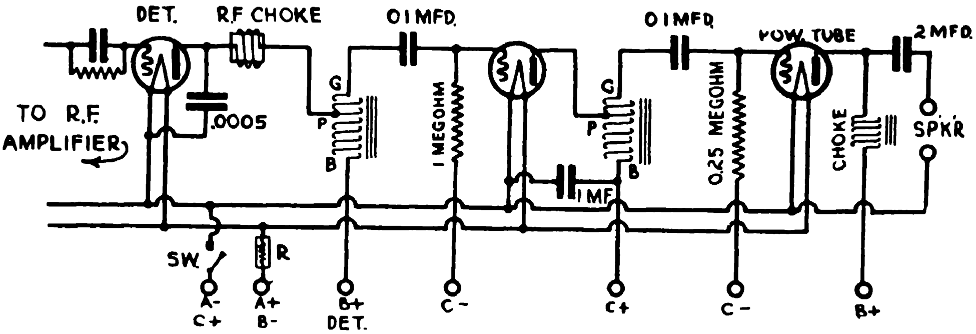


Fig 319—Typical 2-stage auto-transformer coupled amplifier circuit arrangement

introduced into the grid circuit makes the total amplification greater than for straight impedance coupling, with the advantage that strong signals do not block the grid. Very good reproduction is secured if the plate coil has an inductance of at least 100 henries, and a blocking condenser of about 0.1 mfd. is employed. In some dual-impedance coupling units, very good low-note amplification is secured without using very large coils and cores, by so determining the inductance of the plate and grid coils and the capacity of the coupling condenser that the entire combination tunes or

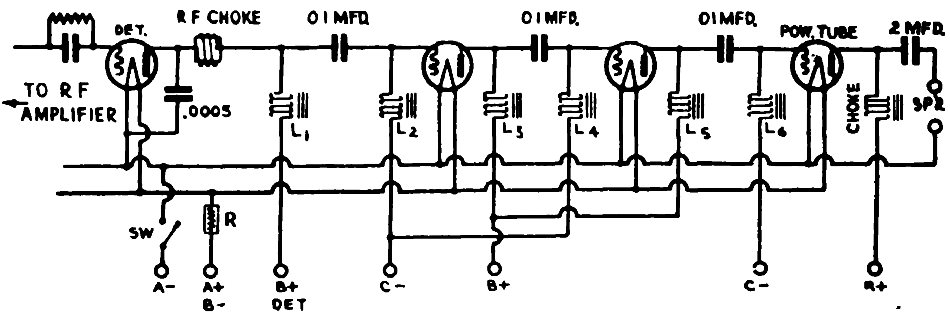


Fig 320—Typical dual-impedance coupled amplifier circuit.

resonates at about 30 cycles. The result is that the amplification of these low frequencies is unusually good. High-mu tubes are usually employed in a dual-impedance amplifier.

439. Combination couplings: Amplifiers are often built with combinations of the coupling devices described, in order to secure certain

desirable characteristics, such as a compromise between the well known high "step-up" of one, with the high "quality" and "power handling capacity" of another. One popular combination has been that of one stage of transformer-coupling and two stages of resistance-coupling. Care should be exercised in the use of such combinations, in order to secure desirable results. The proper relative order of the stages should be considered, to prevent overloading. In a combination of transformer-coupling with any other type of audio-frequency amplification, the transformers should be in the last stages, and the transformer with the highest ratio should be the last one. This tends to prevent overloading of the next to the last tube. Combination amplifiers also show a decreased tendency to motor-boat, since the phase of the transformer stage can be reversed by reversing the connections going to either the primary or secondary winding.

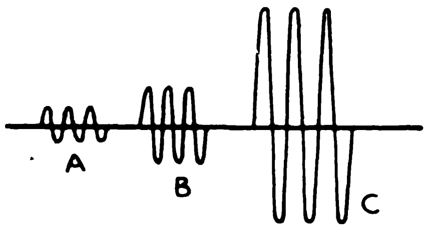


Fig 321—The signal voltage variations are amplified by the successive amplifier stages as shown by the succeedingly larger amplitudes of curves A, B, and C

440. The direct-coupled Loftin-White amplifier: In the direct-coupled amplifier system the plate of one tube and the grid of the next are coupled directly through a common resistor—no blocking condenser and leak resistor being employed. By eliminating these, grid blocking due to strong signals is avoided and the frequency response is improved. The problem of coupling the successive tubes in vacuum tube amplifiers is largely the problem of causing the plate current variations in the circuit of one tube to cause grid potential variations which are as large as possible and unaffected by the frequency, in the following tube. Of course the proper plate and grid bias voltages must be applied. The so-called "resistance-coupled amplifier" discussed in Article 432, a single stage of which is shown in simplified form at (A) of Fig. 322, really resolves itself into a resistance-capacity coupling by reason of the coupling condenser C_1 The reactance of this condenser varies with the frequency, and on low frequencies this reactance is sufficiently large to cut down the frequency response. In this type of coupling also, the effective input capacity C_{gc} between the grid and cathode of the second tube will operate substantially as a shunt across the leak resistance R_g at high frequencies, and will cut the response in the upper range. The plate-cathode capacity C_{pc} of the first tube acting across the plate resistor R_0 also acts the same way. This is larger as the amplification of the tube and associated circuit is increased.

The third fault lies in the fact that there is no voltage step-up in the coupling itself, and thus additional stages are required to secure a desired gain. Also, on strong signals there is a tendency for the grid circuit of the last audio tube to block due to the accumulation of electrons on the grid, and the resulting reduction in the plate current. Direct-coupling schemes have been developed to eliminate the coupling condenser and grid resistor in order to do away with these objectionable frequency-characteristics. This means that a *direct coupling* between the plate and grid circuits must be employed. Arnold proposed a scheme shown in simple form at (B) in which the coupling condenser and grid resistor were eliminated. The plate of the first tube is conductively or direct-coupled to the grid circuit of the next, through the plate circuit resistor R.

Now let us see what the objections to such a system are. It is seen that a common resistance is used in the plate circuit of one tube and the grid circuit of the succeeding tube. In such a case, the entire positive plate potential, less the drop in the resistance, would be applied to the grid of the next tube. Of course the tube cannot be operated satisfactorily as a distortionless amplifier with a high *positive* grid potential, so the "bucking" or "C" battery is used in the grid circuit. This battery must of necessity have voltage enough to cancel the plate battery voltage plus whatever grid bias is required. This would all be very well were it not for the fact that in such a circuit the drop across the resistance R, which is common to both these circuits, is not constant. When a signal is applied to the grid of the first tube, its plate current rises, and consequently the drop across the resistance is greater. This upsets the bias on the grid of the next tube, usually sufficiently to throw the second tube off its operating curve. Should the signal get past the second tube, the effect would be even greater in the next stage. Also, in a system of this nature, there is a "drift effect". That is, if for any reason the current through any tube should change, there is no provision made to restore the state of equilibrium. Consequently, after it has been in operation for a moment or so, the various circuit conditions will drift until the entire system is blocked and no signal can find its way through. Also the battery requirements for such a system are impractical.

E. H. Loftin and S. Y. White reduced the direct-coupled circuit to a practical form, eliminating the necessity for the separate "C" battery and adapting the entire amplifier for practical a-c electric operation. A simplified diagram of the essential arrangement in their system is shown at (C). The sources of filament voltages are omitted for simplicity in this diagram. A single source of voltage is used in the plate circuit (shown by the box), and a single coupling resistance R_c is employed. The "B" current flows from terminal Y through the plate circuit of the second tube to point T and to N. At point N, the plate current of this tube divides, part flowing through the resistor from N to M, and back to B— and the B· power supply unit. The other part flows up through coupling resistor R_c to S, and across the plate-cathode path of the first tube to W, then down through resistor R to M—where it joins the other part which came through the resistor from N to M—and back through the "B" power unit. Point M is the most negative point in the entire circuit. The plate current taken by the first tube flowing through the coupling resistor R_c from N to S causes a voltage drop in it, and point S is therefore negative with respect to points N and T by an amount equal to this voltage drop. Hence the grid of the second tube has a negative grid bias voltage with

respect to the center point T of its filament circuit, due to this ingenious voltage distribution arrangement. Resistor R_c is constant in value, but the plate-cathode impedance of the first tube will vary when the signal voltage is applied to its grid circuit. There is, therefore, a continually varying change in the voltage distribution between the plate-cathode path of the tube and the coupling resistor R_c when a signal is acting on the amplifier. If the plate impedance is large, the drop across R_c will be com-

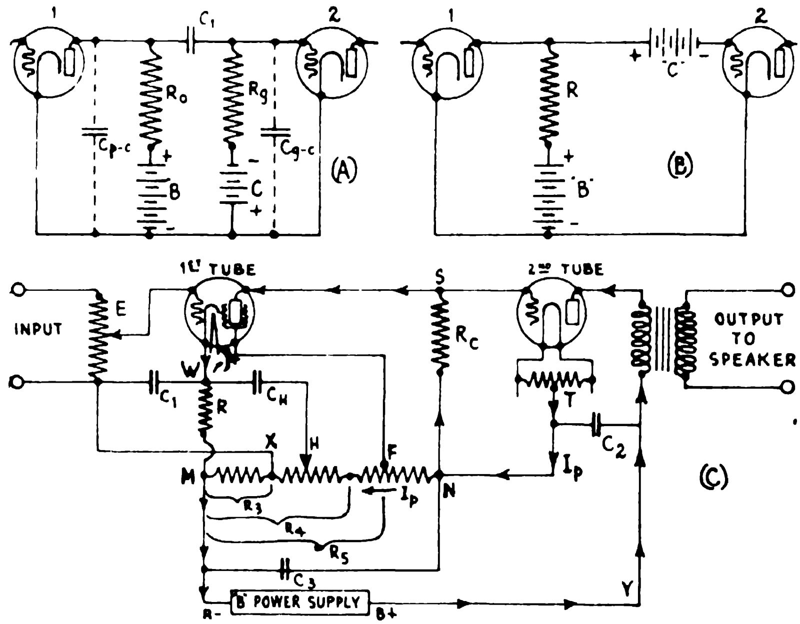


Fig. 322—Development of the Loftin-White direct-coupled amplifier system.

paratively small and vice-versa. When a varying signal voltage is applied to the grid circuit of the first tube, it causes variations in the plate current of this tube: This varying plate current flowing through R_c causes instantaneous variations of the voltage drop across it, which are impressed between the grid and filament of the second tube, and amplified by it. It is evident that the total voltage which must be supplied by the B power unit, is equal to the *sum* of the effective plate voltages actually on the tubes, plus the grid bias voltage (voltage drop in R_c) of the second tube. This means that for given type of tubes employed, the B power unit in this type of amplifier must be capable of supplying a higher voltage than when ordinary forms of coupling are employed.

The voltage drop from N to M through the total resistor is of course the same as the total voltage drop through R_c plus that from the plate to cathode of the first tube plus that in R, since these are two parallel cir-

cuits. Furthermore, each is equal to the entire B voltage, minus the voltage drop in the second tube. A screen grid tube is usually employed as the first tube, on account of its high amplification factor. Since current flows from N to M, by tapping the resistor at a suitable point F, a suitable positive potential, (with respect to the cathode at W), for the particular plate voltage employed, exists across total resistance R_5 and may be applied to the screen grid of this first tube. Resistor R in the cathode-return circuit of the first tube is used as a bias resistor for this. Any tube will have a tendency to increase its plate current when a signal is applied to the grid circuit. As the plate current of the first tube flows through R, the voltage drop across this resistor will tend to increase with the input of the signal. Grid bias resistor R (50,000 ohms for a '24 type tube) for the first tube, is considerably larger than is commonly employed for tubes of this type. There is a definite reason for this. The grid return circuit of this tube is brought back to point X as shown. Point X is at a higher potential than point M by an amount equal to the IR drop in resistance R_3. Also point W is at a higher potential than point M, by an amount equal to the IR drop in resistor R; or, stating this another way, M is negative with respect to W. Now by using suitable values of resistance for R_3 and R, it is possible to make point M more negative with respect to W, than point X is positive with respect to M. Then, point X will be negative with respect to W and therefore the net bias voltage applied to the grid (which is equal to the difference between these two voltage drops) will be negative with respect to the cathode point W.

Perhaps this may be understood more easily by considering points M, X and W, as three men on three different floors of a building, and considering that lower level is negative and higher level is positive. Man M is on the ground floor. Say man W is on the 10th floor. Then he is positive with respect to M by 10 units. X is on the sixth floor. Therefore he also is positive with respect to M, but only by 6 units. But at the same time he is 10 minus 6, or 4 floors under W, so he is negative with respect to W by 4 units.

In this way, a negative grid bias voltage is applied to the first tube and the grid is kept at practically a constant negative value irrespective of the signal input. Any drift effect is also compensated for by this method. The action taking place is very important.

Referring to the diagram at (C), it will be seen that when, for any reason, an increase occurs in the plate current of the first tube, the bias voltage on the second tube increases automatically due to the greater voltage drop in R_6. This causes a decrease in the plate current of the second tube. This latter plate current constitutes the major portion of the current through the resistor from N to M, so that when it decreases, the voltage drop in the resistor R_3 *decreases*. Therefore the net grid bias voltage applied to the first tube *increases*, tending to keep the plate current of this tube constant. This is the important regulation feature of this circuit.

A condenser C_{II}, is connected between the cathode of the screen grid tube and a point H on the voltage divider resistance. The object of this is to introduce a varying hum component voltage into the grid circuit of the tube, of just equal value and opposite phase to that introduced by the varying voltage drop across R caused by any ripple in the plate current, so as to neutralize it and prevent hum. The amount of neutralizating

hum-frequency voltage thus introduced, is varied by an adjustable slider H, arranged to be moved along the resistor until no hum appears in the signal output. Under this condition, the varying voltage drop across R due to the ripples in the plate current, are just equal at every instant to the hum-frequency variation in the voltage drop from H to M. Connecting the condenser as shown, makes these hum voltages oppose and neutralize each other in the circuit between the terminals, at every instant. This hum-bucking arrangement is very effective and important and may be applied in any form of amplifier circuit. It enables satisfactory hum-free operation to be obtained even when rather poor filtration exists in the "B" power supply unit, thereby reducing the size and cost of the filter necessary in this unit. By-pass condensers C_1, C_2 and C_3 are connected across the various resistors to prevent undesirable coupling which might take place.

The advantages of the use of this system are cheapness, low weight, low bulk, high gain and the fact that any frequency can be handled with practically no frequency discrimination or wave-form distortion. The amplifying possibilities are limited only by the amplification constant of the tubes. Of course it is advantageous to use a screen grid tube with its high amplification. Due to the high amplification produced, the output tube chosen must have sufficient capacity to handle, without distortion, what the system will apply to it. The output tube is merely a coupling tube between the amplifier and the loud speaker. It must be built to handle *power*. Even with a single screen-grid tube ahead of it, a large size power tube such as the '50 type should be used in the last stage if the large amplification of the screen-grid tube is to be used. Otherwise the input or the amplification of the first tube must be materially decreased in order to prevent overloading of the last tube. Usually, lower voltages must be employed on the screen grid tube than are specified in the table of Fig. 214, simply because of the limited grid-swing which the following tube can handle. Thus, when a '24 type tube is followed by a '45 type, since the '45 type can only handle a signal voltage of about 40 volts on its grid, the plate, grid and screen voltages used on the preceeding '24 type tube must be less than if, say, a '50 type tube followed. The plate current of the '24 tube under the conditions of operation existing in the usual amplifier of this type is only a few microamperes.

Heater types of amplifier tubes are more convenient in the utilization of the voltage distribution existing in the direct-coupled amplifier because the cathodes of the various tubes are independent of each other. With filament types of tubes, the filaments of all the tubes are connected together in the "A" supply, and so it is difficult to apply the voltage distribution system outlined herein. When applying this system to a practical amplifier operated from the a-c electric light circuit, several precautions are necessary in the design.

For instance, even though the filaments of the tubes employed are all designed to operate at the same voltage, say 2.5 volts, it is necessary to operate the filament of the

power tube from a separate 2½-volt winding of the power transformer. Any attempt to run this filament from the same 2½-volt winding that operates the heaters of the other tubes will result in trouble. The cathodes of the rest of the tubes are practically at ground potential, or at best, at only a small bias above ground. If, then, we proceed to connect their respective heaters on to the power filament winding, we will be placing the same high-voltage-to-ground on to the heaters of these other tubes as we have on the filament of the power tube. This high voltage to ground on the heater is liable to break down the insulation between it and cathode, which is practically grounded since it is only at a small potential above the ground point M. Such breakdowns will ruin reception and the tube. This point is important. Even if this insulation were perfect, there is still another trouble which necessitates the separation precaution. The heater, though only used for its heat, can also be a plate circuit for the electrons given off from the heated cathode. The number of these electrons reaches a real value when the heater becomes positive with respect to the cathode, the condition is excessive when this heater is allowed to reach any such value as say 180 volts positive with respect to the cathode, which it might reach in an actual amplifier. This current would result in fictitious bias voltages in both the power tube and the cathode circuit of the first tube. Consequently in all amplifiers of this type, the filament voltages for the individual tubes are supplied by separate windings on the power transformer.

The direct-coupled amplifier has perhaps found its greatest application in public-address work for amplifying the output of microphones, phonograph pickups, or talking moving picture equipment. Commercial units for this purpose are described in Arts. 547 and 548 in the chapter on Sound Amplifier Systems. By proper design, it is possible to build a two-stage amplifier having a voltage gain of 450 or more. The frequency response may be made flat from 30 to about 7,000 cycles. At higher frequencies, it begins to droop due to the plate-cathode capacity of the input tube and the grid-cathode capacity of the output tube acting across the coupling resistor, but the response can be made uniform to about 10,000 cycles by employing special forms of neutralization. The output stage may be made of the push-pull type for greater signal-handling capacity as we shall see later when discussing power amplifiers.

441. The last audio stage: Every vacuum tube has a certain definite operating range over which its $E_g - I_p$ characteristic is fairly straight, and over which changes produced in the plate current are proportional to the changes in voltage applied to the grid circuit. If the signal voltage is small enough so it produces grid potential swings which cause the tube to operate wholly over this part of its characteristic, and which do not make the grid positive at any time, the amplifier tube itself will not cause noticeable distortion. Now in an audio amplifier, or a radio receiver as a whole, the signal voltage is being amplified in each stage, somewhat as shown in Fig. 321. Assume that the signal e. m. f. input to the first amplifier tube is represented by curve A. After passing through the first amplifier stage the amplified voltage applied to the second stage is as shown in curve B. If it passes through still another stage it becomes stronger, as shown in curve C. Since each stage amplifies the voltages more, the amplitude of the signal e. m. f. may become so great by the time it is impressed on the grid of the last audio tube that it may either swing the grid potential beyond the linear portion of the

characteristic curve—see curve E at (B) of Fig. 244—and therefore introduce distortion of the wave-form, or it may exceed the grid bias and cause distorting grid currents to flow while the grid is positive. This may take place even though the correct plate and grid bias voltages are being applied to the tube. It is simply a case of *overloading* of the tube, resulting in distortion of the wave-form of the signal. Overloading of the radio-frequency amplifier tubes rarely occurs, as the input signal voltages existing in it are small. Overloading of the tubes in audio amplifiers is common—especially in the last or "output stage", and has led to the development of special tubes known as *power tubes*, designed to have a characteristic curve which is sensibly straight for comparatively wide swings of grid potential (when proper load impedances are used). They are therefore able to handle larger signal voltages without overloading and distortion. (Note: The student is advised to review Arts. 340 to 344 at this point.)

It will be instructive at this point to study the characteristics of the various power tubes listed under the heading *power amplifiers,* in Fig. 214. By referring to the grid-bias voltage column, an idea of the signal voltage amplitude, which each tube can handle without driving the grid positive, may be seen. (The maximum permissable grid voltage swing in either direction is equal to the negative grid bias voltage.) Notice that the large '50 type power tube can handle an 80-volt grid voltage swing, a '45 type can handle 48.5 volts and the '47 type power pentode tube can handle 16.5 volts. However, for a given output the pentode does not need as large an input signal voltage as the others, since it has a greater "power sensitivity". Referring now to the column marked "maximum undistorted output in milliwatts," the relative output powers which these tubes can handle without distortion, is seen. For ordinary home use, the '45 and '47 type tubes are popular for the last audio stage. For powerful amplifiers and other special purposes the '50 type tube is employed, since it is capable of handling a greater signal voltage and can supply a greater amount of undistorted power to the loud speaker. Where more handling capacity than a single tube can provide, is required, it is common to connect two output stage tubes in *push-pull* in order to divide the load. This is often an advantage instead of using a tube having a larger watts rating, for as will be seen from Fig. 214, the higher the rating of a power tube, the higher the plate voltages and currents it requires. This greatly increases the cost of the B power supply unit required, so it is usually much cheaper to use two of the smaller tubes in push-pull instead. This connection will be studied later in Art. 447.

442. Power tubes: Since the function of the last audio tube or tubes in a radio receiver is not only to amplify the signal voltages applied to the grid circuit, but also to supply as much undistorted electrical *power* to the loud speaker as possible with a given input signal, *power tubes* are designed with special characteristics suitable for this purpose. It is the electrical power which the power tube supplies to the loud speaker that is

converted into sound by the speaker. In this respect, the requirements for tubes used in the output stages of radio receivers differ from those used in the other amplifier stages, since the latter are not called upon to supply power, but merely to amplify signal *voltages* applied to their grid circuits. It will be seen from Fig. 214, that tubes having various output power ratings are available. Those used in battery-operated receivers employ rather low plate voltages and pass low plate currents, so their power handling capacity is in general much less than the tubes designed for use in a-c operated receivers where higher plate voltages are more economically available. Since the large power tubes such as the '45, '47 and '50 type must handle quite large plate currents, they are constructed larger than the others in order to dissipate the heat developed in them. A summary of the undistorted power outputs of some popular power tubes is given in Fig. 336.

In the case of the three-electrode tubes, the larger power handling capacity is obtained at the expense of amplification factor, since in order to design a tube of this type with low plate resistance, the relative spacing between plate and filament, and grid and filament, is reduced so the amplification factor is less, as explained in Article 314. Thus, it will be noticed from Fig. 214, that while an ordinary general-purpose amplifier tube of the '27 type has a mu of 9 and a plate resistance of 9,000 ohms, a small power tube like the '71 type has a mu of only 3 and a plate resistance of only 1850 ohms. The larger '50 type tube has an amplification factor of 3.5 and a plate resistance of 1850 ohms. By means of the five-electrode pentode tube construction, (see Articles 317 to 320), whereby the secondary emission is effectively reduced, a much higher amplification factor is obtained, but the plate resistance is also high. Thus, the '47 type pentode tube has a mu of 90 and a nominal plate resistance of 35,000 ohms.

443. Maximum power output: The power output of a power tube is measured in watts or *milliwatts*, whereas the voltage output is measured in *volts*. The voltage output might be very high, but if the plate current were small, the power output of the tube in watts (volts× amperes) would still be small. Let us consider the circuit of a tube supplying power to a load of some kind connected in its plate circuit. This might be the winding of a loud speaker as at (A) of Fig. 323, or the pri-

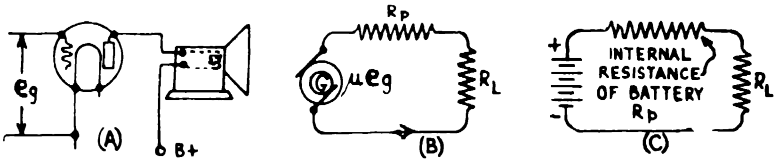


Fig. 323—Arrangement of the plate circuit of a power tube supplying power to a device connected in its plate circuit The essential parts of the circuit are shown in schematic form at (B)

mary of a speaker-coupling transformer as at (B) of Fig. 325, etc. A signal voltage having an "effective" or r. m. s. value of e_g is applied to its grid circuit. At (B) of Fig. 323, the plate circuit of the tube is drawn in the simple schematic form which we found helpful in previous tube discussions. The r. m. s. signal voltage acting on the grid is replaced by the a-c generator whose voltage is μe_g, acting directly in the plate circuit,

where μ is the amplification constant of the tube. The internal a-c plate resistance of the tube is represented by R_p and the impedance of the plate circuit load is R_L.

We must remember, that it is the current *changes* or *variations* due to the signal which supply the motivating power to the loud speaker and cause motion of its diaphragm. A steady direct current sent through the speaker coils would produce no motion or sound, no matter how large it was. The amplitude of the current changes in the plate circuit will be equal to the amplified voltage changes (μe_g) acting in the plate circuit, divided by the total resistance and impedance in the plate circuit, thus:

$$\text{Varying plate current} = \frac{\mu\, e_g}{R_p + R_L}$$

The varying voltage acting across the load is equal to the load impedance multiplied by the varying current through it, that is,

$$e_L = \frac{\mu\, e_g\, R_L}{R_p + R_L}$$

The power in watts ($W = E \times I$) expended in the load impedance is therefore equal to the product of the r.m.s. values of current and voltage. Therefore the power output is:

$$\text{Power output} = \frac{\mu\, e_g\, R_L}{R_p + R_L} \times \frac{\mu\, e_g}{R_p + R_L} = \frac{R_L\, \mu^2\, e_g^2}{(R_p + R_L)^2}$$

This equation is fundamental for all vacuum tubes, assuming the tube to be operating on the straight portion of its characteristic, i.e., that the plate and grid voltages are properly adjusted. It can be shown, both mathematically and experimentally, that the *power output* for any given signal input voltage is a *maximum* when the a-c plate resistance R_p and the load impedance R_L are equal. Under this special condition, the equation for *maximum power output* reduces to:

$$P = \frac{\mu^2 e_g^2}{4R_p}.$$

Note: The dissipation of maximum power in one of two resistors or impedances connected across a source of voltage may be illustrated by the simple case of a battery of internal resistance R_p, with external resistance R_L connected across its terminals as shown at (C) in Fig. 323. If the external resistance were made equal to zero, the battery would be short-circuited. The available potential difference at its terminals would be zero under these conditions and all the power would be dissipated in its internal resistance, producing heat there. Under this condition, the useful output power is zero. If the external resistance is made very large, the current is small, and consequently the useful power in the resistance is small. If the resistance is now decreased in value in steps, a point will be found where the power of the battery is equally divided between the external resistance and its own internal resistance. This takes place when the external resistance and its own internal resistance are equal. This same condition holds true in a vacuum tube or in any circuit in which a source of e. m. f. supplies power to a load.

If the above equation is to be expressed in terms of maximum or *peak* signal voltages, then remembering that the effective value of a voltage or current equals .707 times the maximum value, or equals the maximum value divided by the square root of 2, this expression becomes:

$$P = \frac{\mu^2 E_g^2}{8R_p}$$

Where P is the maximum power output obtainable when a signal voltage having a peak value of E_g is applied to the grid circuit of the tube.

The power which is fed into the load resistance must come from the B-voltage source, because the tube itself does not generate power. It merely acts as a sort of valve in which the variations in signal voltage applied to the grid circuit allow more or less power to be drawn from the "B" voltage source and expended in the plate circuit. Working on the above basis, we can conclude that a '45 type tube for instance, which has an a-c plate resistance of 1750 ohms, will supply maximum output for any given input signal voltage, when the load resistance is 1750 ohms. A '50 type tube having an a-c plate resistance of 1800 ohms will supply maximum power to a load resistance of 1800 ohms, and so forth.

444. Maximum undistorted power output: In radio circuits we cannot consider merely the *power output of a tube*, for the problem of distortion is of equal importance. Numerous tests have shown that a limit of about 5 per cent may be set upon the distortion permissible in a power tube circuit. Distortion under this value will not be noticeable by the average human ear. Now we found at (A) of Fig. 210 that the behavior of a vacuum tube is such that the operating characteristics are somewhat affected by the load impedance, a low impedance shortening the straight portion of the characteristic by causing it to curve more. This occurs, and distortion is introduced, if a load impedance as low as the plate resistance of the tube is used. It has been experimentally determined that the *maximum undistorted* power output of the tube is obtained for any given input signal voltage, when the load impedance is equal to about twice the plate resistance of the tube when the plate current is at its peak value. The power output when $R_L = 2R_p$ becomes $P = \frac{\mu^2 E_g^2}{9R_p}$. This is very little less than the maximum power of the previous equation. The result is in watts if E_g is the peak value of the signal voltage in volts applied to the grid. This voltage is limited to a value approximately equal to the grid bias voltage, if tube overloading is to be avoided. Even with the load impedance equal to twice the tube resistance, there is considerable curvature at the bottom of the characteristic. Therefore, input voltages high enough to make the plate current too low must not be applied, for the lower bend may be reached at signal voltages which are not even nearly strong enough to drive the grid positive. In the case of pentode power

tubes, since the plate voltage-plate current curves are not parallel throughout the operating range of the tube, it should be remembered that the a-c resistance of the tube should be considered when the plate current is at its *peak value*. Thus a pentode tube whose a-c plate resistance at its normal operating point is say 40,000 ohms, may have an a-c resistance of only 5,000 ohms at the peak value of a grid swing so that the load impedance for maximum undistorted power output is 5,000 × 2, or 10,000 ohms and not 80,000 ohms as might be supposed.

The '47 type pentode tube has, compared with a 3-electrode power tube, quite a high a-c plate resistance at normal grid potential, yet for maximum undistorted power output it should work into a load impedance of about one-fifth this normal rated a-c plate resistance. Since no usable load such as a speaker circuit can have a constant output impedance, and as speaker impedances actually rise with frequency, the output of the pentode will increase with frequency. This is a particularly desirable characteristic in a very selective radio circuit, such as a superheterodyne, where considerable high-frequency suppression, in the form of sideband cutting, may exist if a

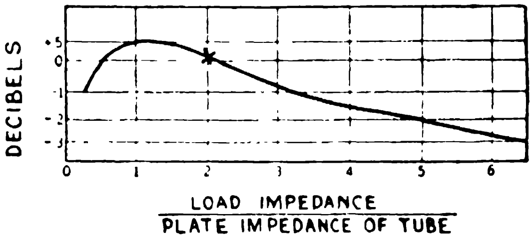


Fig 324—Curve showing how the *ratio* of the load impedance to the plate impedance (or a-c plate resistance) of the tube affects the *total power output* of the tube, for a given input

high order of selectivity is to be realized. The output rising as frequency increases, with the pentode, provides excellent compensation in such a circuit—not enough in itself it is true, but sufficient to simplify considerably the problem of complete equalization when coupled with an audio amplifier and speaker of corrected design. It actually permits an extremely selective and well designed superheterodyne to be built to show a flatter audio response curve up to over 4,000 cycles than has in the past been possible even with the best of t-r-f receivers. Quite some mismatching of the load impedance with the a-c plate resistance is permissable, provided the former is greater than the latter. The curve in Fig. 324 indicates relatively in decibels, (according to the way the ear would be affected), how the total power in the load, (not undistorted power), varies as the ratio of the load impedance to the tube's a-c plate resistance is changed. The "X" on the curve indicates where a tube is normally operated, the load impedance at this point being twice the a-c plate resistance. Statements are frequently made to the effect that the loud speaker used must be matched to the tube to get the largest amount of undistorted power into the loud speaker. Such is the case, but the curve indicates that there can be considerable mismatching without serious loss of power. For example, even when the load resistance is about five times greater than the tube's resistance, there is only a 2 DB loss—a loss which would hardly be noticeable to the ear.

It is unwise, however, to work a tube into a load resistance less than its own a-c plate resistance, because under such conditions the tube's characteristic is curved and this curved characteristic introduces distortion due to harmonic frequencies generated by the tube.

Now it is evident that since the conditions for *maximum power output* and *maximum undistorted power output* are different. If the tube is actually operated with a load whose impedance is equal to twice its plate resistance in order to obtain maximum undistorted output, the maximum

amount of power it is capable of putting into the load for any given signal voltage, will not be obtained. Actually the power is reduced about 11 per cent.

Actually a decrease in power output of 25 per cent would be just noticeable to the ear and therefore a decrease of 11 per cent will not cause trouble. Circuits using power tubes are therefore designed on the basis that the load resistance will be equal to twice the a-c plate resistance of the tube. This condition is always assumed in plotting tube characteristics and in all tables of tube characteristics will be found a column headed, "Maximum Undistorted Power Output" which indicates the power output of the various tubes when they are worked into a load resistance equal to 2R, (two times the plate resistance).

Power tube distortion is more prevalent at the low frequencies than at the higher ones. One reason for this is that since there is greater energy in the low notes, the grid potential is swung further when a low note is being received than when a high one comes in, causing overloading. Also, the loud speaker winding has impedance which varies with the frequency, becoming low at low frequencies. In some cases this may become lower than the tube resistance, with resulting distortion due to curvature of the characteristic. The solution of course is to use a power tube which is able to handle the greatest input signal voltages which will be encountered. Preferably, it should also have a low internal a-c plate resistance so that the load impedance will, at the lowest audio frequency received, be larger than the a-c plate resistance of the tube.

445. Impedance-adjusting methods: The fact that the actuating winding of the usual loud speaker is not a pure resistance, but is really an inductive reactance (capacitive reactance in the case of the condenser-type speaker), complicates the problem of efficiently connecting a loud speaker to a tube. Since the impedance of a loud speaker varies with the frequency, what we do in practice is to pick some impedance which gives a good characteristic and work out the necessary design of the remainder of the circuit using this value of impedance. In working with most magnetic type speakers for example, we assume that the effective impedance is about 4,000 ohms, although actually the impedance varies from about 2,000 ohms up to 30,000 ohms, or so. Since the a-c plate resistance of most power tubes (see Fig. 214) is in the neighborhood of 2,000 ohms, the speaker impedance of 4,000 ohms is just suitable for the condition of maximum undistorted output. However, as we shall see, an output filter device is sometimes used between such a speaker and the tube to keep the direct plate current of the tube out of the speaker winding.

The moving-coil system of the modern electro-dynamic loud speaker has a very low impedance, usually around 10 or 20 ohms. This raises the problem of how we can work such a loud speaker out of ordinary power tubes which usually have an a-c plate resistance of about 2000 ohms, and still get a large amount of undistorted power output for any given input signal voltage. This difficulty is solved by the use of a transformer which has the very useful characteristic of permitting us to make a 10-ohm moving-coil act as though its impedance was 1000 or 5000 ohms, or any

other impedance we might choose. How this is accomplished will now be shown.

A general expression may be derived for the turns-ratio of an "impedance adjusting" or "matching" transformer for coupling a source of power and a load in the most efficient manner, for any circuit conditions.

Thus in (A) of Fig. 325, let E_p be the voltage applied to the primary of the impedance adjusting transformer T by the source of power G, whose internal impedance is R_G. Let the load, whose impedance is R_L, be connected to the secondary winding as shown. Let N_p be the number of turns on the primary winding and N_s the number of turns on the secondary. Now to obtain maximum power transfer from the generator G to the primary of the transformer, R_G must equal R_p. This then determines the design of the primary winding. The power which the primary takes from G is converted by means of the magnetic field into power in the secondary winding, so that the secondary really becomes the source of power for the load. For maximum

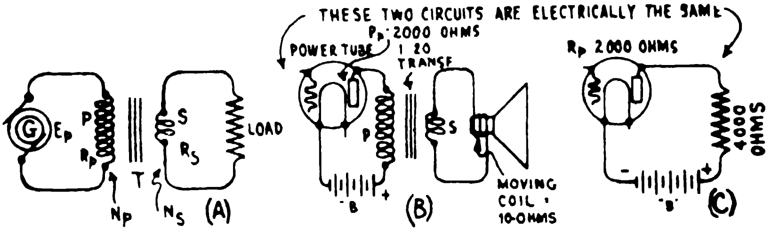


Fig 325—Use of a transformer with proper primary impedance and impedance ratio as an impedance adjusting transformer

power transfer from the secondary to the load, the impedance of the secondary must equal that of the load, that is, R_s equals R_L. Let I_p and I_s be the primary and secondary currents respectively. Then, by simple transformer action we have,

$$\frac{N_s}{N_p} = \frac{E_s}{E_p} \tag{1}$$

and,

$$\frac{N_s}{N_p} = \frac{I_p}{I_s} \tag{2}$$

multiplying the left hand parts of the two equations together, and doing the same with the right hand side will not change the equality. Doing this we obtain,

$$\frac{N_s}{N_p} \times \frac{N_s}{N_p} = \frac{E_s}{E_p} \times \frac{I_p}{I_s} = \frac{E_s}{I_s} \times \frac{I_p}{E_p}$$

Now in each case, $E/I = R$. Therefore this reduces to.

$$\left(\frac{N_s}{N_p}\right)^2 = \frac{R_s}{R_p} \tag{3}$$

That is, the ratio of the two impedances equals the square of the ratio of the turns. This relation greatly simplifies the problem of determining the turns ratio required to adjust the impedances of any two circuits for satisfactory operating conditions.

Let us now apply this to a practical tube problem. Suppose a '45 type tube has a plate resistance of 2,000 ohms and is to supply power to a moving-coil loud speaker, the effective impedance of the moving-coil being 10 ohms. The circuit arrangement is shown at (B), of Fig. 325. For maximum undistorted power output for any given signal voltage, the load impedance should be twice that of the tube, or 4,000 ohms in this case, since the source is the amplifying tube. In this case, the primary of the impedance-adjusting transformer forms the load for the tube, so its impedance

is to be 4,000 ohms. We want to work into a loud speaker whose impedance is 10 ohms. For maximum power transfer from the secondary to the loudspeaker, their impedances should be equal. Therefore the impedance of the transformer secondary should be 10 ohms. Hence, from equation (3) we obtain:

$$\text{turns ratio}^2 = \frac{R_s}{R_p} = \frac{10}{4,000} = \frac{1}{400}$$

from which, the turns-ratio equals 1/20 or .05. This means that, if we take our 10 ohm loud speaker winding, and connect it to the secondary of a 1 to 20 ratio transformer, which has enough turns on the primary so its impedance is 4,000 ohms, then the primary may be connected in the plate circuit of the 2,000 ohm power tube and the entire circuit will operate just as though the loud speaker had an impedance of 4,000 ohms, (the correct load impedance for a 2,000 ohm tube) and was connected directly in the plate circuit, as shown at (C). It will be noticed that the "impedance adjusting" or coupling transformer ratio has been referred to in the same way as for ordinary transformers, i.e., the ratio of the *secondary* to the *primary* turns. The source of power fed to the impedance-adjusting transformer is called the "source". The device into which the secondary feeds the power is called the "sink". It is evident then that the impedance-adjusting transformer is simply a device designed so its primary absorbs power most efficiently from the source, and its secondary delivers this power (which is transferred to it by electromagnetic induction from the primary) most efficiently to the sink. The primary of the coupling transformer for loud speakers should be wound with sufficient primary turns so its primary impedance is equal to 2 times that of the a-c plate resistance of the power tube at the lowest frequencies to be received, provided this value of the impedance is practical from the point of view of cost and distributed capacity of the winding. The value is really not critical. In the case of the push-pull connection of audio output tubes, the plate resistance of the two tubes combined is equal to twice that of one tube alone, (see Art. 447). Therefore, the load impedance should be made equal to twice this, i.e., equal to 4 times the a-c plate resistance of one tube.

Impedance "adjusting" transformers are used extensively in radio and telephone work for coupling power tubes to loud speakers, for coupling phonograph pickups to inputs of amplifiers, for coupling power tube outputs to low-impedance lines and then coupling the low impedance lines to higher-impedance lines or loud speakers, etc. We will study some of these applications in our later work. In any case, the design of the coupling transformer is arrived at in the same way as has been explained here.

446. Output coupling systems: There are in general, three main types of loud speakers in common use. These are, the electrostatic or *condenser* type; the *coil* type; and the *permanent magnet* movable-arma-

ture or diaphragm type. The coupling of the condenser type to the power output tubes of a radio receiver presents a special problem which will be considered when that type of speaker is studied. The moving coil type commonly known as the electro-dynamic speaker employs a moving coil of such low impedance (10 ohms or so) that an impedance adjusting transformer must always be employed to couple it to the plate circuit of the power tube for satisfactory power transfer. This is true for both the electro-dynamic and permanent magnet dynamic types of speakers. As this system has already been discussed in Article 445, and shown in Fig. 325, it will not be considered again here. In speakers which employ permanent magnets for producing the steady magnetic field, there are usually one or more coils of wire through which the signal current flows. These produce variations in the main magnetic field of the permanent magnet and the construction is arranged so that this varying field moves an iron armature or reed, whose motion is transmitted to the diaphragm or cone which produces the sound waves. This type of speaker is commonly referred to as the "magnetic speaker" although a moving coil speaker is also a "magnetic speaker", properly speaking. The problem of coupling this type of speaker to the output power tubes of a radio receiver presents several problems which we will now consider.

The coils on these magnetic type speakers must have a large number of turns of wire, (two or three thousand turns), in order to provide a field which will be effective in causing motion of the armature or reed. Since the variations in the plate current of the last audio tube are not very great, when considered in terms of *amperes*, these coils must have a large number of turns of wire in order to have an effective number of *ampere turns*. In order to use the large number of turns required for proper operation and sensitivity, it is necessary to use very small, enamel-covered copper wire, since only a very limited space is available for the windings. The very fine wire employed is usually unable to continuously carry the *direct* plate current of the larger sizes of power tubes without undue heating and eventual burn-out. Therefore some means must be provided to keep the total direct plate current out of the speaker windings if it is more than about 10 milliamperes, and allow only the variations or a-c signal component to act on them. The steady direct component of the plate current does not produce any motion of the diaphragm anyway, so it can be kept out of the speaker. It is only the audio-frequency variations in the plate current which produce the motion. Another reason for keeping out the direct plate current, is that this current may be made to flow through the speaker windings in either one of the two directions depending on how the speaker terminals are connected in the plate circuit. With one arrangement the direct plate current flowing through the coils produces a steady field in such a direction as to aid the magnetism of the permanent magnet. However, if the speaker terminals are connected in the opposite order, the field will buck that of the permanent magnet continuously and weaken it. The possibility of connecting it in the latter way

is another reason for keeping this current out of the speaker winding.

Another reason is that this current flowing through the winding produces a field which deflects the armature or reed from its neutral position and thereby makes it much more liable to strike the pole pieces of the magnet when strong signals are being received, resulting in "rattling". This condition is neither necessary nor desirable.

There are in general two common methods of keeping the direct com-

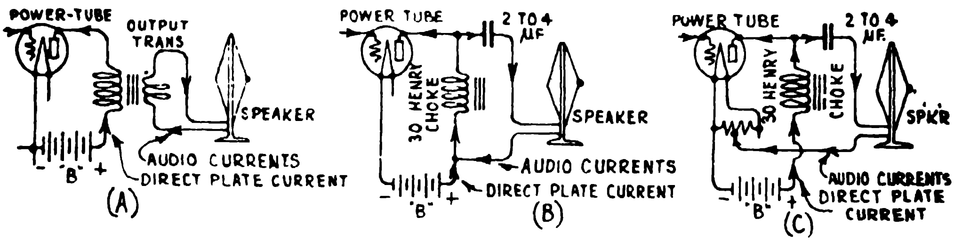


Fig 326—Three loudspeaker coupling systems for keeping the steady direct component of the plate current of the tube, out of the fine-wire loud speaker winding.

ponent of the plate current out of the speaker winding. In the first, a coupling transformer is employed; in the second a form of choke coil-condenser coupling is used. The first method is shown at (A) of Fig. 326. Here a coupling transformer commonly called an *output transformer* is employed with its primary connected in the plate circuit of the output tube and the loud speaker connected across its secondary. Since the induced voltages in the secondary are produced only by the *variations* in the plate current, the output in the secondary is an alternating voltage and current and is not affected by the direct component of the current through the primary. The objectionable operating conditions described above are thereby eliminated by its use.

Accurate data on the impedance characteristics of all types of magnetic and dynamic speakers is not available, but the usual type of magnetic speaker has a coil winding having a d-c resistance of from 1,000 to 2,000 ohms with an impedance which varies from that value at zero frequency (d-c current flowing through the windings), to a value of about 2,500 ohms at 100 cycles, 5,000 ohms at 300 cycles, 10,000 ohms at 750 cycles, 20,000 ohms at 1750 cycles and up to 30,000 or 40,000 ohms at the higher frequencies up to 5,000 cycles per second. These high values of impedance for this type of loud speaker unit are due to the comparatively high inductance of the wi. ding which is made up of a large number of turns. Now we found in Article 444 that for minimum undistorted power output from a 3-electrode vacuum tube the load impedance should be equal to about twice the a-c plate resistance of the tube. If a power amplifier tube having an a-c plate resistance in the neighborhood of 2,000 ohms is employed, the impedance of a speaker of this type will be fairly well matched to the

plate resistance of the tube to fulfill this condition for maximum undistorted output, and the coupling transformer may have a 1 to 1 impedance ratio, i.e., it has a turns-ratio of 1 to 1. As we are not limited by space considerations in the size of wire used in the primary of such a transformer, it can be designed to have sufficient carrying capacity to eliminate danger of burnout due to the flow of the plate current of the power tube. However, since this direct plate current tends to produce saturation of the core, the cores of such transformers are usually provided with a suitable air-gap. If a speaker of this type is to be fed from a power amplifier tube having a plate resistance in the neighborhood of 4,000 ohms or more, it is evident that in order to secure the proper 2 to 1 impedance relation at the low frequencies, the output transformer must be designed to adjust the impedances as explained in Article 445. In this case, its turns-ratio will be something other than 1 to 1, and the coupling transformer acts as an impedance-adjusting device as well as to keep the direct plate current component out of the speaker windings

Another popular coupling system for magnetic speakers is shown at (B) of Fig. 326. In this, an a-f choke coil is connected directly in the plate circuit of the power amplifier tube and the speaker winding is connected across it through the series blocking-condenser as shown. The varying plate current flowing through the choke coil produces varying voltage drops across it, (assisted by the self induction of the choke), so that due to the signal, the potential of the plate varies up and down from its steady normal no-signal value. This voltage variation is applied in the circuit consisting of the speaker winding and the condenser in series, so that a transfer of electrons takes place from one condenser plate to the other through the speaker winding, the B power supply unit and the plate-cathode path in the tube. This flow of electrons of course constitutes a flow of electric current varying at the audio frequencies at which the plate current of the tube varies, i.e., at the frequencies of the audio signals, so the speaker produces sounds corresponding to these The paths of the direct plate current and the audio current are shown in (B). It should be remembered that while the choke and condenser coupling system does serve the purpose of keeping the direct component of the plate current out of the speaker winding, it does not act as an impedance adjuster, unless a tapped choke is used. Where impedance adjustment is necessary, it is cheaper and more advantageous to use a coupling transformer of proper design.

The arrangement of (B) sometimes leads to trouble due to coupling in the "B" power supply unit, because the varying audio currents flowing through it may cause variations of potential across impedances common to the circuit of the output stage and those of the other amplifying stages. This often causes 'howling" or "singing". There are several variations of this circuit arrangement, but the one shown at (C) is probably the most satisfactory. In this, the series combination of condenser and choke is

returned directly to the filament or cathode circuit of the tube. In this way, a direct path is provided for the varying audio current so it does not flow through the B-power supply, thus preventing the undesirable common coupling which often results with the schemes of (B). If the filament of the power amplifier tube is heated with d-c, the speaker-return lead can be brought directly to the negative filament terminal. If the filament is operated by raw alternating current from a transformer, the speaker return should be brought to the electrical center of the filament. This can be done by either returning it to a center tap on the transformer filament winding, or to the center tap of a fixed resistance connected across the filament as shown Another advantage of the connection at (C) is that since one end of the speaker connects to the filament, (or B minus), and the other end is isolated from the plate—so far as direct potential is concerned—the speaker terminals have no high voltage on them at all and are perfectly safe to handle. It must be noted, however, that the full "B" potential is placed directly across the speaker circuit to the negative return. This means that the condenser must be of the high-voltage type. A shorted condenser would put the full "B" voltage through the speaker, by way of the choke, with the result that the speaker windings would probably burn out in time

The capacity of the condenser should be as high as possible (it should not be less than 2 mfd.), to avoid resonance peaks in the loud speaker response and should have a breakdown voltage rating safely above the plate voltage to be applied to the tube. The choke coil inductance should be as high as possible so as to offer a very high impedance to the passage of the signal current through the choke. An iron-core choke coil of 30 henries inductance is commonly used for this purpose. This is wound with many turns of wire on a "core" or "shell" type laminated silicon steel core. The higher the ratio of impedance of the choke to the combined impedance of the condenser and loudspeaker, the greater will be the proportion of signal current in the loudspeaker circuit and consequently the greater the volume produced by the loud speaker for a given signal input to the amplifier. The values are not critical, however. In some cases, two condensers are connected in series with the speaker, one on each side. The special coupling arrangements used when a push-pull output stage is employed will be studied in connection with push-pull amplification.

447. Push-pull amplification and wave-form distortion: We have found in our study of audio amplification and the action of the vacuum tube as an amplifier, that distortion of the wave-form of the a-f input signal voltage can take place due to the tube itself. As a result of this distortion, the wave-form of the plate current variations is not exactly similar to the wave-form of the signal voltage variations impressed on the grid circuit. Therefore, the sound waves created by the movement of the diaphragm of the loud speaker to which these plate current variations are fed, will not be a true reproduction of the wave-form of the original

signal voltage variations, and the sound output is said to be *distorted.* The four ways in which wave-form distortion may take place in an amplifier tube have already been discussed in Arts. 339 to 344, but they will be reviewed here briefly, as they are very important in the consideration of the push-pull amplifier connection. As already explained, frequency distortion may take place in tube-coupling devices, but it does not occur in the tubes.

Let us consider a typical "static" grid voltage—plate current characteristic of a vacuum tube operated with a high impedance in the plate circuit, as shown at (A) of Fig. 327. It curves over at the upper region C, curves under at the lower region A, and is sensibly straight at the middle portion B. If the plate voltage, grid bias and filament voltage are adjusted properly, so that the "no-signal" operation point is at the center, B, of the straight portion, (which is the proper operating point for an amplifier tube), then a signal voltage 0-1-2-3-4 of medium value applied to its grid circuit will produce plate current variations 0-1-2-3-4 having exactly the same wave-form as shown. Since this plate current wave-form is exactly the same as that of the applied signal voltage, no distortion is produced by the *tube* under these condi-

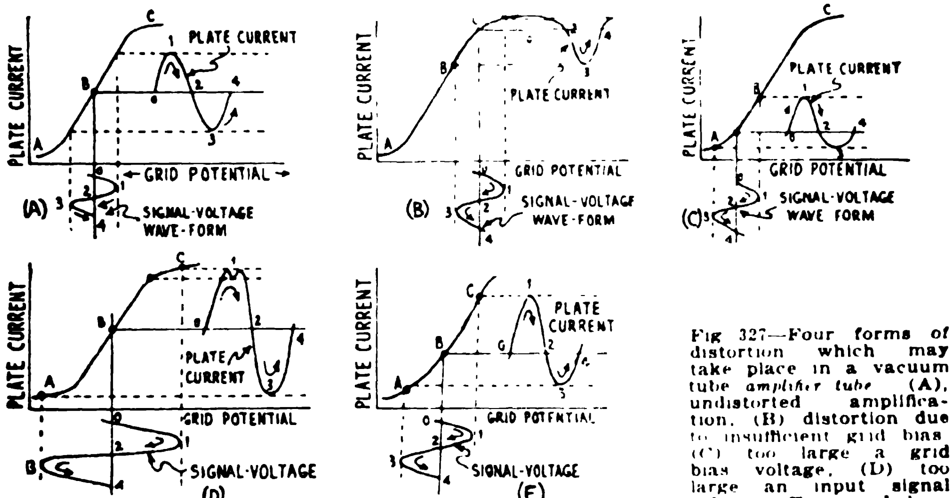


Fig 327—Four forms of distortion which may take place in a vacuum tube *amplifier tube* (A), undistorted amplification, (B) distortion due to insufficient grid bias (C) too large a grid bias voltage, (D) too large an input signal voltage, (E) curved characteristic due to too low a plate load impedance. These are forms of distortion which may take place in the tube itself.

tions. For simplicity in our discussion, we will assume that the signal voltage applied to the grid circuit is of simple sine-wave form. Actually of course, the signal voltages existing in the a-f amplifier of a radio receiver are varying in frequency, intensity, and wave-form at each instant, depending entirely upon the pitch, loudness and timbre respectively of the sound acting on the microphone in the transmitting station. The considerations for distortion and action of amplifiers however, are no different for these complicated wave-forms than they are for a simple sine-wave sound or current. The actions of the latter are easier to follow and understand.

If the plate and grid voltages are such that the signal voltage applied to the grid circuit causes it to become positive during each positive half cycle of the signal voltage, or causes it to operate over the upper bend C, of the curve, distortion will be produced as shown at (B). In the former case, current flows in the grid circuit each time the grid is made positive by a positive half cycle of the signal voltage. This results in a voltage drop in the apparatus connected in the grid circuit and so reduces the signal voltage actually affective at the grid. The result is not only a flattening of the upper loop of the plate current variation, but a dip may actually be caused at the peak as shown at (D) of Fig. 328. In the latter case, even if the grid does

not go positive, the mere fact that the tube is operating on the upper bend of the characteristic curve, causes distortion. In either case, the variations of the plate current changes during the positive half cycles of the signal voltage are *less* than those produced by the *equal* negative half cycles. The wave-form of the plate current variations is now different than that of the applied signal voltage variations, so distortion has resulted. As shown at (B), the increases produced in the plate current are smaller than the decreases.

If the tube is operated at the lower bend A, of the characteristic, as shown at (C), the reverse action takes place. As shown in the diagram, even though the positive and negative half cycles of the signal voltage are equal, the corresponding plate current variations are not equal. The decreases in the plate current are smaller than the increases (This is exactly what happens in a grid bias detector, by the way.) Therefore distortion takes place.

If the tube is now operated at the center of the straight portion as shown at (D), and a large signal voltage is applied to the grid circuit so that the grid potential varies over both the upper and lower bends of the characteristic, then the form of the plate current variations is flattened both at the top and bottom of each half cycle, as shown. Due to the grid current flowing when the grid becomes positive, the upper peak of the plate current dips as shown. This of course, also represents distortion of the waveform.

Up to this point we have assumed that the E_g - I_p characteristic of the tube is straight over the center region B. Now this is the "static" characteristic curve and really does not represent the situation under which the tube actually operates. When some form of *impedance* consisting of a loud speaker winding, the primary of a transformer, etc., is connected in the plate circuit, the conditions are somewhat different, as we found in Article 293 and showed in Figs. 209 and 210. Under these operating conditions, the voltage drop in the load impedance at each instant, causes variations in the plate voltage which is actually effective on the tube, and causes the plate current changes to lag the grid potential changes, so that the characteristic becomes curved over a large part and is not as straight as we have supposed.

Now considering the output power tube of the receiver, we know that for a given signal voltage, maximum power is transferred to the load in the plate circuit if the impedance of the load is equal to the plate resistance of the tube. However, for the straight amplifier connection, if the plate load is made of this value, the characteristic of the tube becomes very much curved, as shown at (E) and distortion of the wave-form of the plate current results, as shown. If the load impedance is made smaller than the plate resistance, the curvature of the characteristic becomes more and more pronounced, and severe distortion takes place. Actually, in practice the output load is made equal to about twice the tube resistance in order to reduce this curvature of the characteristic to a point which does not cause objectionable distortion due to this cause. This means of course, that the full power output which the tube is capable of delivering for any given signal voltage applied, is not obtained, but a value less than this, which is commonly called the "undistorted output" is obtained. The push-pull amplifier circuit eliminates the distortion effects of the curved characteristic and therefore enables us to use a lower load impedance in the plate circuit—one which is nearer to the value of the plate resistance of the tube. This means that with the push-pull circuit, for a given signal input voltage applied to the grid, an *undistorted power output* more nearly equal to the *maximum output* available for that signal voltage can be obtained for each tube. This is one big advantage of push-pull. It helps toward enabling smaller size power tubes to be employed in the last audio stage for a given output. The use of the smaller power tubes means that lower "B" voltages are employed and a saving in the cost of the "B" power supply unit is effected. Its other advantages such as larger signal-voltage-swing handling capacity, elimination of hum caused by a-c current ripple, elimination of necessity for a by-pass condenser across the grid-bias resistor, and cheaper construction of the output transformer will be pointed out as we proceed.

Before proceeding with the detailed study of the push-pull action, let us see just how "harmonics" enter into the wave-form distortions shown in Fig. 327. During our study of sound waves in Article 6, we found that "harmonic", or "multiple", frequencies are very common in speech and musical sound waves and are really the cause of the different quality or

timbre which enables us to distinguish one musical instrument from another when a note of the same frequency is played. We found that the "second harmonic" is a sound wave of double the frequency of the fundamental wave. Now when dealing with sound, since the device which produces the sound introduces the harmonic frequencies which determine its wave-form, the harmonics are not looked upon as forms of distortion for they really are part of the distinguishing character of the sound. We speak of such sound waves as are shown in Fig. 14, as being "complex",

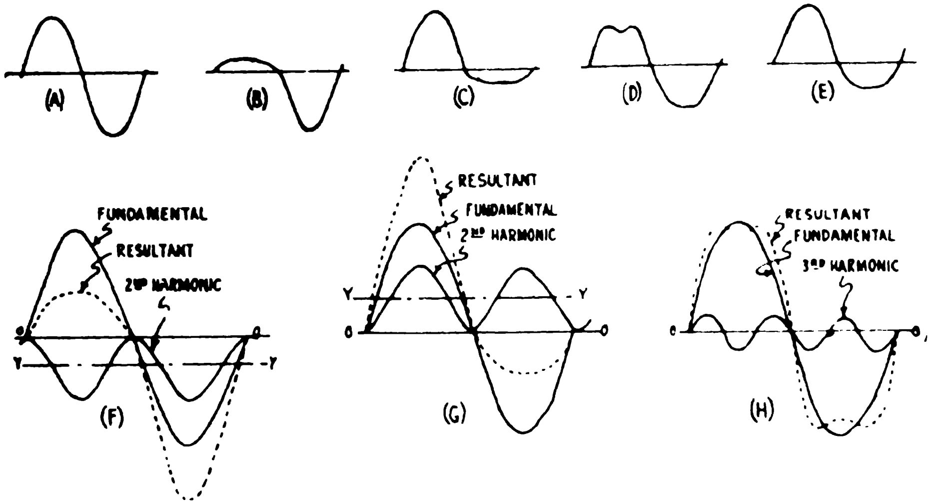


Fig 328—How the distorted wave-forms in Fig 327 may be duplicated by considering them to be equivalent to the sum of a fundamental sine wave, and second or third harmonic sine waves

due to the harmonics, but we do not consider them as distortions However, when harmonic frequencies which are introduced into electrical circuits or sound waves by a vacuum tube or any other device, are of an undesirable nature and were not present in the original sound itself, the waves resulting from the combination of the harmonics with the original waves are said to be *distorted*. We found that distortion of the plate current variations in a vacuum tube amplifier could be produced by operating the tube improperly, and by its curved characteristic Let us see how harmonic frequencies enter into this.

If we consider the simple sine-wave input signal voltage again with a symmetrical wave-form as shown at (A) of Fig 328, we find from Fig 327 that if the grid bias of the tube is insufficient, the curve representing the variations in the flow of the output plate current is distorted to the form shown at (B) of Fig. 328. If the grid bias is too large, the distorted plate current wave is as at (C). If the grid bias is correct, but the input signal voltage is too great, the wave is distorted as at (D). If the characteristic is curved due to a plate circuit load of too low an impedance, the

wave is distorted as at (E). Now the distortion of the plate current waves at (B), (C) and (E) is of the same character. Our study of distorted wave shapes of this sort may be greatly simplified by considering that instead of having in the circuit, a single current or voltage which varies in value as shown by the wave-form, we have a pure sine-wave of the same frequency as the distorted wave, (this sine-wave is known as the *fundamental*), plus pure sine-waves of frequencies which are multiples of the fundamental frequency. The latter are of the *harmonic* frequencies. Let us fix this matter firmly in our minds before we proceed any further. Even though we speak of a distorted wave voltage or current, as containing harmonics, it does not necessarily mean that these harmonics exist as separate waves, voltages, or currents distinct from the distorted one, but rather the effect or action of the distorted one upon the circuit is exactly the same as if it were replaced by one of the fundamental frequency and associated harmonics all of simple sine-wave form. This should always be kept in mind. Now referring to the distorted wave-forms at (A) and (B), we can consider them to be equivalent to a sine-wave fundamental plus a sine-wave second harmonic which is entirely above or below the zero axis. The axis of the second harmonic is Y - Y. The three wave-forms drawn together, are shown at (F). At every point along the "O-O" axis, the amplitude of the fundamental plus the height of the second harmonic (with due regard to direction above or below the axis), is equal to the height of the resultant wave-form. Therefore, the fundamental plus the second harmonic of these relative strengths are equivalent to the resultant distorted wave-form, and this wave-form is exactly as shown at (B). Consequently, since the resultant distorted wave-form is obtained by combining a pure sine-wave of the same frequency with a second harmonic wave, we usually say that the distortion is due to the second harmonic present, and that if the second harmonic were eliminated, the pure undistorted wave-form would result. At (G), the combinations to produce the distorted wave-form of (C) and (E) are shown. Notice that (F) and (G) are similar in shape excepting that they are 180 degrees out of phase. At (H) we have the combination of a fundamental sine-wave with a third harmonic sine-wave of smaller amplitude, to produce the resulting symmetrical distorted wave-form which has a dip at each peak. This will be seen to be similar to the wave-form distortion produced by the condition of (D) in which the grid going positive causes a flow of current in the grid circuit. The distortions represented by (B) and (C) will never occur in a well designed amplifier, in which the proper grid bias voltage is applied to the grid. That at (D) may occur if signals which are stronger than the permissible grid swing of the tube used will allow, are applied. That at (E) is very likely to occur unless we are satisfied to use a very costly, high impedance load in the plate circuit of the output tube and be satisfied with the reduced power output which will result. We can consider that these wave-form distortions of (B), (C) and (E) are caused by parasitic second harmonic current variations set

up in the plate circuit of the tube, since they are similar to the conditions shown at (G) and (F). The condition of (D) is a combination of second harmonic and a weak third harmonic distortion. Consequently, our problem is one of eliminating the effects of the second harmonics.

If a certain distorted wave-form can be conveniently considered as the sum of a fundamental and say even number (2, 4, 6, etc.) harmonics, it must not be supposed that absolutely no odd number harmonics (3, 5, 7, etc.) exist, but rather that the maximum amplitude of any odd harmonics that must be added to give exactly the original distorted wave form is so small compared to the maximum amplitude of these

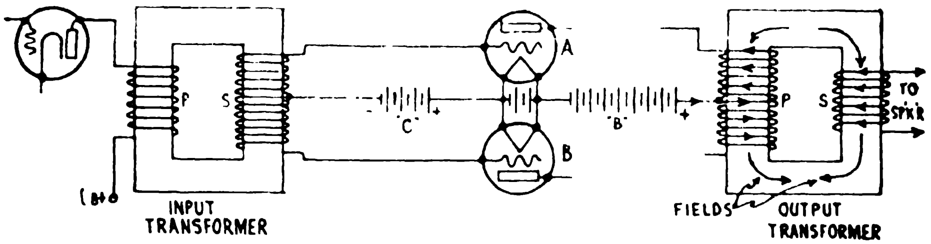


Fig 329—Typical push-pull amplifier stage showing instantaneous directions of currents and voltages

even harmonics necessary, that the odd harmonics may be neglected. The reverse is true regarding a distorted wave-form containing a predominance of odd harmonics.

Now assuming that the objectionable wave-form distortiors which we have found to exist in a vacuum tube operated as an amplifier—especially in the last audio stage—are caused mainly by second harmonics, let us see how the push-pull tube connection eliminates them. A typical circuit diagram of a simple-push-pull connection of amplifier tubes is shown in Fig. 329. This connection is usually employed in the last audio stage of the receiver, but it may also be used in the r-f amplifier, or in any of the other audio stages.

For convenience, the diagram is drawn for battery operation, and the usual input and output transformers are shown with rectangular iron cores so that the instantaneous directions of the voltages, and currents may be more clearly shown. The input transformer consists of a primary wound to have a satisfactory impedance to work out of the plate circuit of the preceeding tube. The secondary S, wound in the same core with the primary, has a tap at the *electrical center* of the winding, i.e., at the center point considered from the "induced voltage" standpoint. Each end of the secondary connects to the grid of a tube, the center tap connects through the grid bias voltage source to the cathode. The primary of the output transformer is also tapped at its electrical center, the midpoint connecting to B+ and the two ends connecting to the plates of the tubes. It is wound to have the proper impedance for efficient transfer of power from the plate circuit of the tube. The secondary is usually a single winding as shown, wound on the same core. Now let us see how this combination operates. The C battery places a certain definite value of negative bias voltage on the grid of each tube. This is the proper value to set the operating point at the middle of the straight portion of the characteristic. Since the plate voltage source is also common to both tubes, if they are matched, i.e., have similar operating characteristics, the same plate current will flow through both. Now when no signal is applied, since the equal plate currents flow through the equal halves of the primary of the output transformer in opposite directions as shown, they produce equal and opposite magnetomotive forces which neutralize each other. Therefore there is no magnetic field

in the core due to the steady direct component of the plate currents. This is one important inherent advantage of the push-pull circuit which we shall consider again later.

Now let us see what happens when a signal voltage is applied to the amplifier. A varying current flowing in the primary of the input transformer produces a varying magnetic field which induces a corresponding varying voltage in the entire secondary. As each half of the secondary is connected across the input circuit of a separate tube, the total induced signal voltage in the secondary of the input transformer is divided, each tube receiving an input grid voltage equal to only half this signal voltage. This point is important for it means that any two tubes in push-pull can handle twice as much *total* input signal voltage, without operating on the bends of the characteristic curve, as one of these tubes alone can.

Let us now see what happens during each half cycle of the signal voltage applied to the grids. Suppose that at a certain instant the voltage induced in the secondary of the input transformer is such that the grid of the top tube "A" becomes positive with reference to the center-tap of the transformer secondary, and the center tap is equally positive with reference to the grid of the lower tube "B". (This does not mean that the grid is "positive" with reference to its filament, for in this event distortion would be produced due to the flow of grid current. The "C" battery voltage is greater than any signal voltage that may be applied, so the grids are always *negative* with respect to the *filament* or cathode. It merely means that due to the signal voltage, the grid of tube A, becomes less negative than it was before and the grid of tube B becomes more negative.) This will cause the plate current of tube A, which flows

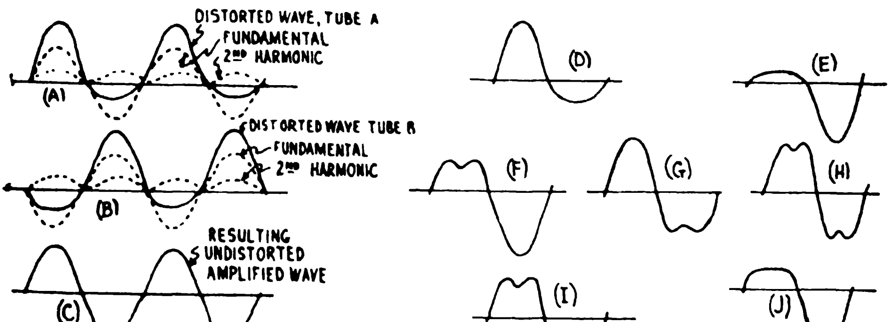


Fig 330- How the distorted plate current wave-form in the push-pull amplifier combines in the output or choke to eliminate second harmonic distortion

through the upper half of the output transformer primary, in the direction shown by the arrows in Fig. 329, to increase. At the same time, the plate current of tube B, decreases an equal amount. Since these currents both flow in opposite directions in the output transformer primary, as shown, the effect of changes of opposite nature in the plate current or of the two tubes is *additive* both as regards change of "magnetism" in the core, and

"voltage" induced in the secondary winding. That is, if at one instant the current in the upper half of the primary winding (plate current of tube A) *increases*, the magnetic field produced by it *increases* correspondingly. If *at the same instant*, the current in the lower half of the primary (plate current of tube B) *decreases*, the magnetic field produced by it *decreases*. Under these conditions, the fields produced by the two halves of the primary winding no longer equal and neutralize each other, but there is a resultant field in the direction determined by the direction of flow of the larger current. For the particular conditions and instant mentioned above, this is downward in the left leg of the core as shown by the arrows on the core. This resultant field therefore induces a voltage in the secondary in such a direction as to tend to oppose this increase (Lenz's law of electromagnetic induction). The direction of the secondary voltage and the field produced by the secondary current are shown in Fig. 329. Therefore, the effects of the varying signal voltage, on the plate currents of the two tubes, are *additive in the output transformer.*

On the next half cycle of the signal voltage, the induced voltage in the secondary of the input transformer reverses, the lower end now becoming more positive and the top end more negative. Therefore, the plate current of the tube B, increases and that of A decreases. The net magnetic field is now in the opposite direction and so a voltage is induced in the secondary in the opposite direction to that induced before. This appears across the terminals of the secondary. This action is repeated during each cycle, first the plate current of one tube increasing, and that of the other tube decreasing and vice-versa—hence the name "push-pull".

Now let us first suppose that the correct grid bias voltage is being applied to the tubes and a value of sine-wave signal voltage is applied, such that it does not overload the tubes. Then due to the curvature of the characteristic (caused by the plate load impedance), the plate current changes of tube A, will vary according to the distorted wave-form shown at (C) of Fig. 328 and at the same instant that of tube (B) varies in accordance with the wave-form of (B). These wave-forms for two cycles have been drawn again, directly under each other in Fig. 330 for convenience, the top one being for the tube A, and the next one for tube B. Now as shown previously, each of these distorted wave-forms can be considered to be replaced by a fundamental and second harmonic as shown by the dotted curves. It will be noticed that the fundamentals in the two *tubes* are 180 degrees out of phase and the second harmonics are in phase. It will be evident by referring to these current directions at any instant that the fundamentals, which are 180 degrees out of phase with each other in the plate circuit (one increases while the other decreases), add together in the output unit (whether it be a choke coil or a transformer), since an increasing current through the upper half of the winding produces the same induction effect as a decreasing current in the lower half. For the same reason, the harmonics (which are in phase with each other) in the plate circuit neutralize each other in the output unit and the resultant output to the loud speaker is an amplified reproduction of the fundamental wave only. This is an undistorted sine wave-form in this case, similar to that of the input voltage. It is shown at (C).

Thus the effect of the push-pull connection is to balance out in the output transformer or choke coil, the second harmonic distortion produced by the tubes. Any second harmonic distortion which may exist in the wave-form of the signal voltage which is applied to the amplifier is not balanced out by the push-pull stage however, since the secondary of the input transformer applies this distorted wave-form and the second harmonics to the inputs of the tubes 180 degrees apart. Therefore they add together in the output transformer and are still present in the output and are passed on to the loud speaker. Consequently, while a push-pull amplifier stage will correct the second harmonic distortion produced by its own tubes, it will not correct any which might have been caused by a previous amplifier stage, or which may be caused by apparatus which follows it. For the same reasons, any second harmonics existing in the input signal voltage due to the sound program itself, are not eliminated.

If the two tubes were operated with too large a value of negative grid bias voltage, the plate current wave-forms of the two tubes at any instant would be as shown at (D) and (E) of Fig. 330. Since this is a case of second harmonic distortion only, it would be corrected in the output transformer. However, if too low a value of grid bias were applied, each grid would swing positive during each half cycle on loud signals, and the grid current flowing would produce the dips in the plate current wave-forms as shown by curves (F) and (G) of Fig. 330. The push-pull system does not eliminate the third harmonic, as the reader will readily see by following through the actions of the system for third harmonics. Therefore the second harmonic distortion only is removed in this case and the resulting current delivered to the loud speaker is of the distorted form shown at (H) of Fig. 330. The dip in the peaks indicates third harmonic distortion. The magnitude of the third harmonic that is usually present is small enough to be neglected.

If a large signal voltage be applied to the grids of both tubes such that the grid potentials swing over the upper and lower bends of the characteristic, the plate current variations of each tube are as shown at (I) and (J) of Fig. 330. The resulting current (as at H) contains a large third harmonic distortion, which is passed on to the loud speaker.

It is evident that with balance conditions, no fluctuating audio signal current flows down through the "B" power supply line, since the increase in the plate current of one tube just equals the decrease in the plate current of the other at each instant. Therefore, the total plate current supplied by the "B" circuit remains constant. Therefore, no audio coupling can take place in the impedance of the B power supply, so far as the push-pull stage is concerned. This reduces the possibility of instability due to feed-back voltage variations from the power tube plate circuit to that of the detector or first audio tube, and also greatly reduces the possibility of "motorboating".

A complete circuit diagram for a two-stage audio amplifier arranged for a-c electric operation and employing a push-pull output stage is shown in Fig. 331. This may be employed either as the audio amplifier in a radio receiver, or as a "phonograph" or small "public-address" amplifier. It will be noticed that the automatic grid bias method is used for the push-pull stage, grid bias being obtained by connecting the grid bias

resistor R, in the plate return circuit between the center tap of the filament resistor and the negative terminal of the B power supply unit. If both tubes have the same mutual conductance and output resistance no condenser is necessary across this automatic grid bias resistance, for the reason that the plate current variations will always be equal and 180° out of phase. The sum of both currents will then always be a constant. Since there is no a-c component in the plate current, no by-pass condenser is necessary.

If both tubes of a push-pull amplifier are not matched, so that the mutual conductances are not the same, then the plate current variations of the two tubes flowing through this grid bias resistance will be unequal

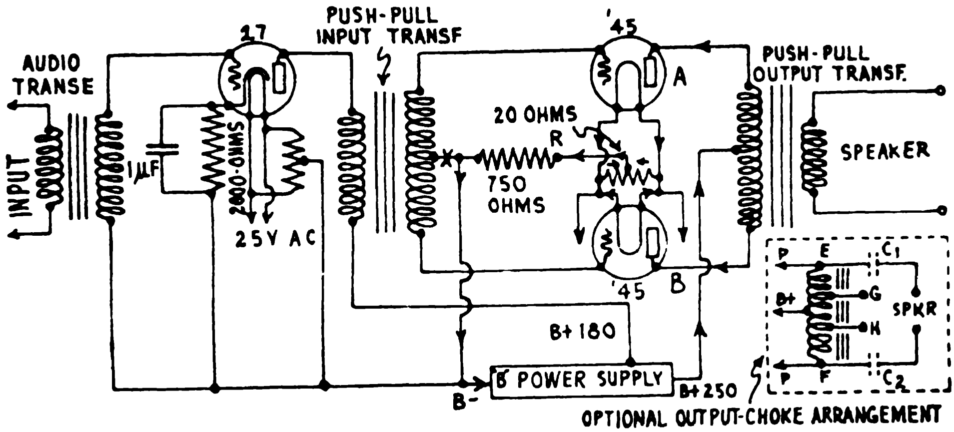


Fig. 331—Typical 2-stage transformer-coupled audio amplifier circuit with push-pull output stage. The amplifier is arranged for a-c electric operation. The actual amplifier is shown in Fig. 333.

and 180° out of phase. The result will be an a-c component which can be by-passed with a condenser in the usual way if desired, but it is really not necessary. If this by-pass condenser is omitted, the voltage across the grid bias resistance will vary. This variation will be 180° out of phase with the grid voltage of the tube having the greater variation of plate current (greater mutual conductance) and in phase with the grid voltage of the other tube. In other words, the tube having the greater mutual conductance will receive *degenerative* action while the other tube will receive *regenerative* action, the tubes tending to divide the load equally. Thus the effect of the mis-matching of the tubes is not so serious.

This will be understood by referring to Fig. 331. Suppose the mutual conductance of tube A, is greater than that of tube B. Also suppose that at one instant the signal voltage applied to A is increasing in a positive direction while that of B is increasing in a negative direction. The increase of plate current of A would be greater than the decrease in plate current of B, resulting in an average increase of voltage drop across R. The grid bias then becomes more negative. The increasing bias is in phase with the increasing negative signal voltage of B, producing *regenerative* action and at the same time being 180 degrees out of phase with the signal voltage of A pro-

ducing *degenerative* action. Thus one tends to equalize the other. Regenerative action means an action which helps the applied signal voltage. Degenerative action opposes the signal voltage. The circuit connections for a push-pull output stage employing pentode tubes is shown in the circuit diagram of Fig. 283.

Inspection of Fig. 331 shows that any plate current ripple caused by incomplete filtration in the B power supply unit will affect the plate currents of both tubes equally and in phase. Therefore the effect automatically cancels out in the primary winding of the output transformer. This means that since not so much filtration is required, the filter in the B supply unit can be made more simple and cheaper.

Push-pull amplifiers are apt to oscillate in some cases, due to energy feedback by some path. To prevent this condition, a high resistor of from 10,000 to 50,000 ohms should be connected in the input transformer center-tap grid-return lead, at the point marked "X" in Fig. 331. This should *not* be by-passed with a condenser. The amplifier can be tested for oscillation either by listening for the howl or whistle which accompanies it, or by connecting a low reading milliammeter in the "C"— leg at point "X" in order to determine whether any current is flowing in the grid circuit. Under normal conditions there should be no deflection of the needle. However, if the circuit is oscillating, several milliamperes of current may be found to flow in the grid circuit. Then the remedy described above should be applied.

The center tap on the secondary of the input transformer need not be located exactly at the electrical center, for any slight unequality in the voltages applied to the grids, due to a slightly off-center tap will automatically be taken care of by the degenerative action of the plate current of the tube obtaining the larger signal voltages, somewhat in the same manner as already described for the grid bias resistor case. The center tap on the output transformer should be accurately located at the electrical center of the winding however, for any inequality here will not only cause a magnetic flux in the core due to the direct component of the plate currents, but will also result in incomplete balancing of the second harmonics, with resulting distortion of the output current. So far as the current from the "B" power supply unit is concerned, the plate circuits of the two tubes are in *parallel*, and the total current it must supply is equal to the sum of the plate current taken by each tube. So far as the *variations* in plate current are concerned, the path consists of the primary of the output transformer in *series* with the plate-to-filament circuits of the two tubes, for the plate current variations due to the signal exist only in this path. Therefore the impedance of the primary of the output transformer must be designed with this fact in mind. The plate impedance of the push-pull combination is taken as equal to the sum of the plate impedances of the two tubes, due to this series path condition. In the push-pull circuit, since the two d-c plate currents in the two halves of the primary flow in opposite directions; the resultant magnetization of the core is very small. Since the two halves of the windings are connected "series aiding" so far as a-c currents are concerned, the total inductance is increased. This means that not only less iron, but less copper as well, can be used for a given inductance value in a push-pull output transformer or choke than would be used for a single tube output device. The air gap in the core should not be dispensed with altogether;

it should simply be reduced. An air gap should be used in order that the original high value of inductance effective at small values of a-f may be maintained at high signal levels.

The output unit in a push-pull amplifier may be either a choke coil, as at the lower right of Fig. 331 or a transformer, as in the main diagram.

When a choke coil is used, with well matched tubes, (passing the same plate current) the ends of the winding E and F are at substantially the same D. C. potential, for there will be the same potential drop from the common center tap to E and F. For this reason the speaker can be connected across these points without danger of any damaging direct current flowing through the windings. This eliminates the necessity for any blocking condensers between the choke and the speaker. However, fixed condensers C_1 and C_2 of 2 to 4 mf. capacity are sometimes connected in the speaker circuit in order to insulate the speaker terminals from the high plate voltage to prevent severe shock if they are touched by a person whose body is grounded. This is especially advisable when the larger power tubes such as the 210 or 250 types are employed, as the voltages then are above 300 volts.

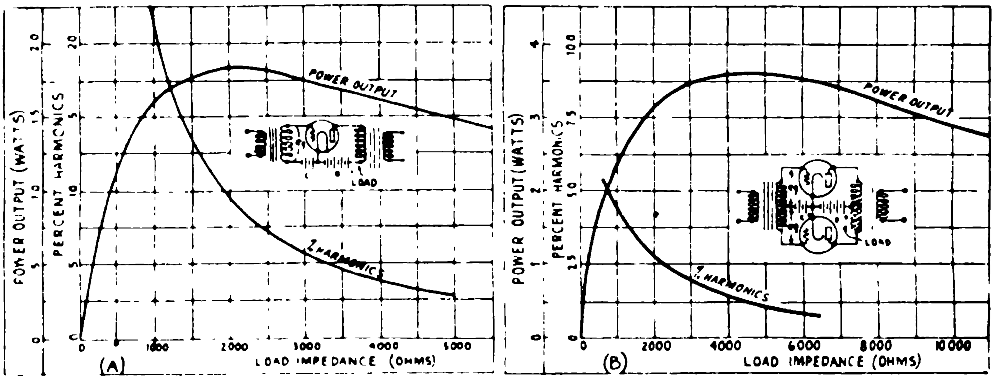
Some push-pull output impedances are made with two taps. Points G and H are at the same d-c potential when placed equally distant from the center tap. They may be used for speaker connection when a step-down impedance ratio is required for the best operation of low-impedance speakers, such as for feeding directly into the 10 or 15-ohm voice-coil of an electro-dynamic type loud speaker The use of an output transformer is perhaps more popular than the choke for push-pull circuits In most cases the secondary is designed to work directly into the 10 or 15-ohm voice-coil of the electro-dynamic speaker employed.

Maximum power output is obtained from a tube when the load impedance equals the a-c plate resistance of the tube. If the load impedance is made equal to the tube resistance in a straight amplifier, maximum output will be obtained, but the percentage of the second harmonic present due to the curvature of the characteristic prohibits the use of this one-to-one ratio. The ratio of load impedance to tube resistance is usually made about 2 to 1, in order to minimize the second harmonic distortion. This is shown very clearly by the graph at (A) of Fig. 332 (reprinted here by courtesy of *Electronics Magazine*) in which the power output and per cent second harmonics are plotted for various values of plate load impedance (or a-c plate resistance), for a typical three-electrode power amplifier tube having an a-c plate resistance of about 2,000 ohms and having a signal voltage as large as it is permissible to apply without working over the bends in the characteristic, applied to its grid circuit.

The power output curve shows that greatest power output (about 1.8 watts) occurs when the load impedance is made equal to 2,000 ohms, which is the same as that of the tube. Since a harmonic distortion up to about 5 per cent is not considered objectionable in practice, it is seen that the 9 per cent distortion which results if this optimum value of load impedance is used, is very high. If the load impedance is made equal to 4,000 ohms (twice the plate resistance of the tube), about 1.6 watts or 90% of the maximum power output possible is obtained, and the harmonic distortion is reduced to the low value of about 3.5 per cent—which is permissable.

Now contrast this with the curves at (B) which are drawn for the push-pull output stage using the same type of tubes and operated at the same voltages. The same signal voltage is applied between the grid and filament of *each* tube in this case, as was applied to the single tube just discussed. It is seen that the maximum power output of 3.6 watts is obtained when the plate load of 4,000 ohms (equal to the plate resistance of the tubes in push-pull) is used. Since the distortion due to harmonics is only 1.3% for this operating condition, the conditions for undistorted output are being satisfied and this may be considered as the *maximum* undistorted output also. Notice that this power output is 3.6 watts as against 1.8 watts for the similar case with the single

tube, i.e., just twice as much. Therefore for a given signal input voltage applied to the grid of *each* tube, and a given allowable distortion, the push-pull connection puts twice as much *undistorted output power* into the load, as the single tube does. This demonstrates forcibly the advantage of the push-pull connection over the single output tube connection in the matter of wave-form distortion due to harmonics. It also illustrates the fact that since the harmonic distortion is so low with the push-pull connection, the load impedance may be made equal to the effective plate resistance of the tubes in push-pull (twice the plate resistance of one tube), without introducing objectionable distortion. This enables the maximum power output of the tubes to be obtained without distortion. That is, for a push-pull amplifier the terms *maximum power output* and *maximum undistorted power output* (distortion below 5 per cent) mean one and the same thing, whereas for the single tube connection the maximum undistorted power output which can be obtained, is *less* than the *maximum* power output, due to the necessity of using a higher impedance plate load to reduce the har-



Courtesy Electronics Magazine.

Fig 332—(A) Graph showing how the power output and per cent harmonics in a single tube output stage varies for different values of load impedance (or a-c plate resistance) for a tube having an a-c plate resistance of 2000 ohms
(B) Same for a push-pull stage with similar tubes

monic distortion to the traditional "5 per cent maximum" value. If the load resistance is double the total plate resistance of one of the push-pull tubes, then the maximum undistorted power output of a push-pull stage is obtained for a given signal input applied to it. The maximum undistorted power output of *each* tube in watts is then given by the general formula for maximum power output, for the reasons stated above. This is:

$$P = \frac{\mu^2 e_g^2}{4R_p} \text{ or } \frac{\mu^2 E_g^2}{8R_p}$$

Since the total power output of the two tubes in push-pull is equal to the sum of the power delivered to the load by each tube, the maximum undistorted power output for the entire push-pull stage is,

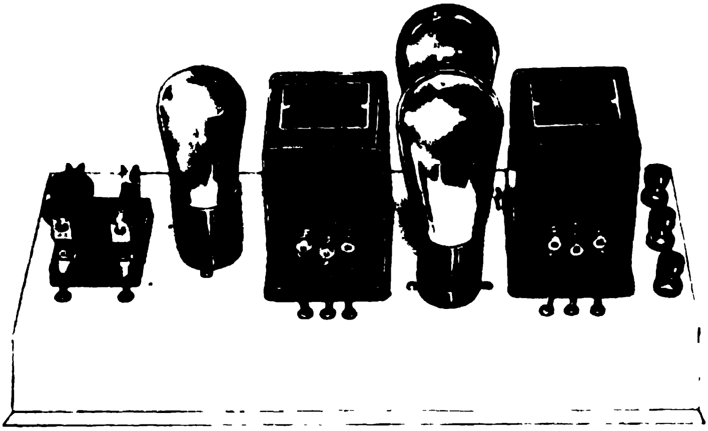
$$P = \frac{\mu^2 e_g^2}{2R_p} \text{ or } \frac{\mu^2 E_g^2}{4R_p}$$

where e_g is the *r. m. s. value* of the signal voltage applied between the grid and filament of each tube (equals one-half the total signal voltage developed across the secondary of the input transformer), and E_g is the *peak* value of this voltage. R_p is the a-c plate resistance of a *single* tube.

When speaking of the turns ratio of a push-pull input transfofmer, the ratio between the turns included between the center tap and one end of the secondary, to those on the primary is meant. Thus a 3 to 1 input transfer has 6 times as many

turns on its entire secondary winding as it has on the primary, or 3 times as many turns between the center tap and either end as it has on the primary. The reason for this is that we are interested in the actual ratio between the voltage applied to the primary of the transformer by the preceeding tube and that applied to the grid circuit of *each* tube considered separately, by half of the secondary winding.

Because of the greater freedom from objectionable harmonics when a push-pull amplifier is overloaded, it is permissable in practice, to apply somewhat greater input signal voltages voltage per tube without serious distortion, than when a single-tube stage is used. Hence the maximum



Courtesy Pilot Radio & Tube Corp

Fig. 333—The 2-stage amplifier with push-pull output stage whose circuit diagram is shown in Fig 331 Resistance input coupling is also used The push-pull tubes and transformers are at the right

undistorted power output obtainable from two tubes in push-pull is usually considered as being equal to about 2.25 times that obtainable from a single tube of the same type, (see Fig. 336). The advantages of the push-pull amplifier circuit may now be summarized as follows:

(A) Elimination of second harmonic distortion originating in the tube circuit. (It does not eliminate second harmonic distortion originating in preceeding or following equipment.)

(B) Twice the permissable grid-swing voltage allowable for a single tube stage may be applied to the push-pull using the same type of tubes. This means that smaller size power amplifier tubes can be used to handle a given total signal voltage. This results in decrease in cost of the "B"-power supply unit.

(C) Reduction of hum when a-c operated. Less filtering is necessary in the "B"—power supply unit. Also, hum-voltages originating in the filament circuit when a-c operated, cancel out.

(D) Elimination of the by-pass condenser across the grid bias resistor. This is especially advantageous when pentode tubes are used, for if a single pentode is employed, a by-pass condenser of about 8 or 10 mf. is required across the grid bias resistor to eliminate serious degenerative effects on the low audio frequencies.

(E) Less iron and copper required in the output transformer or choke.

These advantages have made it a very valuable form of amplifier. The push-pull principle can be adapted to resistance coupling, and the Clough coupling system very satisfactorily.

Fig. 333 shows a two-stage audio amplifier with push-pull output stage. The first tube (at the left) is resistance coupled to the input. Next comes the push-pull input transformer, then the push-pull tubes, and the output transformer is on the right with the output binding posts. The three terminals on the secondary of the input transformer and on the primary of the output transformer are plainly shown. The circuit diagram is shown in Fig. 331. The fact that for equal input signal voltage, a push-pull amplifier stage delivers about twice as much power to the load as a single tube stage would (using same type tubes) does not mean that the sound issuing from the loudspeaker will sound twice as loud. Doubling the power output means a gain ratio of 2 in the power. Referring to Fig. 304 we find that this is an increase of three decibels. One decibel is about the smallest difference that can be detected with the ears. Therefore an increase of three decibles is noticeable, but of course it does not mean that the sound will be anywhere near twice as loud.

448. Dual push-pull amplification: High-gain a-c operated audio amplifiers designed particularly for use in public-address systems, and in sound picture work, frequently make use of two '50 type power amplifier tubes in push-pull in the output stage in order to handle the large signal voltages existing there and to deliver the large amount of power required.

If these tubes are operated at their maximum rated voltages, in order to obtain as much undistorted power output from them as they are capable of handling, a maximum "peak" signal-voltage (in one direction) of about 80 volts must be developed across each half of the secondary winding of the push-pull *input transformer* and applied to the grid circuit of *each* tube. (Note: This is equal to the value of the negative grid-bias voltage, see Fig. 214). Assuming this transformer to have the common ratio of 2 to 1, the signal voltage across its primary would have to be 80 divided by 2, or approximately 40 volts. If the amplifier tube feeding into this transformer has an effective "mu" of 8, then the signal voltage applied to its grid must be about 40 divided by 8, or 5 volts, for this output. To prevent the possibility of overloading, the negative grid-bias for this tube should therefore be at least 6 or 7 volts.

Since powerful amplifiers of this type are usually 3-stage amplifiers, it is common to make both the second and the last stages of the push-pull

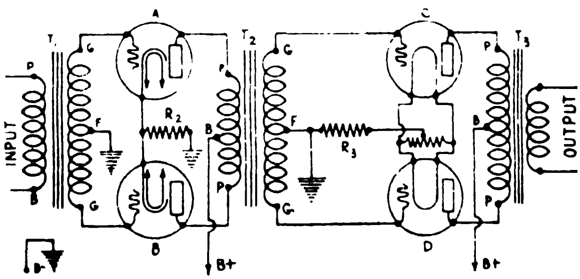


Fig. 334—Typical 2-stages of audio-amplification with "dual push-pull" stages This form of amplifier circuit is commonly used in heavy-duty power amplifiers used in sound amplifier systems

type, as shown in Fig. 334. This is called a ***dual push-pull amplifier.*** **The first stage may be of the single-tube type. The use of the push-pull stages eliminates any "second-harmonic" distortion which might otherwise**

occur in the last two stages, besides providing the other advantages which have already been pointed out during our study of push-pull amplification.

In the circuit diagram of Fig. 334, the special interstage push-pull tranformer T_2 has a center tap on both the primary and secondary windings. The push-pull action is the same as has already been described in Article 447. Push-pull tubes A and B obtain their negative grid bias voltage by the fall of potential in resistor R_2. Tubes C and D obtain theirs by the fall of potential in R_3.

449. Parallel output tubes: Greater undistorted power output handling capability than a single tube provides, can also be obtained by connecting two or more tubes with their grid circuits in parallel and their plate circuits in parallel, as shown in Fig 335. The filaments may

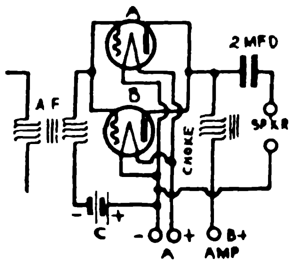


Fig 335—Typical transformer-coupled a-f amplifier circuit with two output tubes connected in parallel

also be connected together in parallel as shown. Evidently it is possible to connect more than two tubes this way if desired, but for the purposes of explanation we will consider the connection with two tubes in parallel Since the signal-voltage variations are applied to both grids simultaneously, both tubes really work in phase. Therefore both the fundamental and harmonic waves are present in the output, i.e., this connection does not eliminate the harmonic distortion caused by the tubes, as the push-pull circuit does. This is one of the objections to the parallel-tube connection.

The amplification constant of the combination is equal to the constant of a single tube if both tubes are similar. If one of the tubes has a high mu and the other a low mu, the resultant amplification of the two is equal to the average of the two mu's. Thus if the mu of one tube is four and that of the other is seven, the resultant amplification constant is 5.5.

For similar tubes, the resultant plate impedance will be equal to half the impedance of a single tube and if unlike tubes are used, the impedance can be calculated from the laws governing resistances in parallel. The greatest power output is obtained when the two tubes have identical plate resistances and amplification constants, but a very large fraction of the total power of the two tubes can be obtained even if they differ greatly. Since the plate circuits of both tubes are in parallel both as regards direct plate current flow and the variations due to the signal, the a-c plate resistance of the combination is equal to half that of a single tube—if both tubes are similar. This makes the output a-c plate resistance rather low. This is sometimes advantageous where the tubes are to supply power to a load of low impedance. For a

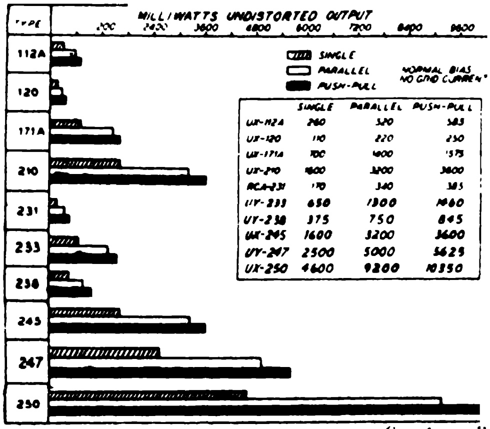
given input signal voltage and 2 parallel tubes feeding into a load impedance equal to twice the combined plate resistance of the tubes in parallel, twice as much undistorted power can be obtained as could be obtained from a single tube feeding into a load impedance equal to twice its plate resistance. The total power delivered to the load in any case, is simply the sum of the powers delivered by each of the parallel tubes.

Possibly the greatest drawbacks to this system are that second-harmonic distortion is not eliminated, and that the maximum peak signal voltage which can be applied to the grids without overloading is equal to that specified for a single tube (about equals to the grid-bias voltage). This differs from the push-pull arrangement, where the allowable total input signal voltage is double that for a single tube, because due to the push-pull connection only half the total input signal voltage actually acts on each tube.

It would also be possible to connect four or more tubes to form a push-pull parallel tube arrangement, with two or more tubes in parallel on each side of the push-pull arrangement. This arrangement secures the benefits of lowered plate impedance and retains the advantage of greater allowable input signal voltage and elimination of tube distortion which is characteristic of the push-pull connection. This would only be resorted to in special public-address or sound-picture amplifiers in which a very large amount of undistorted output power would be required.

450. Output power required: We have seen how the power output delivered by any tube, or combination of tubes, to the load connected in the plate circuit, can be calculated if the types of tubes employed and the signal voltage applied to the grid circuit, are known. The next question which arises is, just how much electrical power is required from the last audio stage? Assuming that the electrical power output from the last amplifier stage drives the diaphragm of the loud speaker, the problem resolves itself into a determination of how much sound power in watts is required to produce the necessary volume of sound, and what the efficiency of the loud speaker is, i.e., how many watts of sound energy it delivers for every watt of electrical energy put into its windings by the amplifier. The answer to this first problem is one which depends upon many conditions such as size of the room, absorption properties of the walls and drapes in the room, volume of sound required, etc., so that no figure which would be true for all cases can be given. The loud speaker efficiency is also a variable quantity. Speakers of different types and manufacture have different efficiencies—unfortunately all very low, as we shall see in the next chapter. The following power values may be considered as giving some basis for average radio reception at the volumes ordinarily used in the home. It may be safely assumed that a power of from ¼ to ¾ of a watt should be supplied to each permanent-magnet type cone speaker employed, and about 1 or 2 watts for each medium-sized electro-dynamic speaker employed. For the large type electro-dynamic speakers designed especially for auditorium work, a power of from 2 to 20 watts may be supplied for full volume. These are average figures given merely to give the reader some idea of how much power must be supplied to the loud speaker. It

may vary greatly in individual cases. In the chart of Fig. 336, are arranged for convenient comparisons, the undistorted power output in watts which the various power amplifier tubes will deliver to loads of proper impedances (see Fig. 214), connected in the plate circuit, (or by a proper impedance-adjusting transformer), when a signal voltage having a peak value equal to the maximum which the tube can handle without overload-



Courtesy R C A Radiotron Co

Fig. 336—Chart showing graphically the maximum undistorted power outputs which may be obtained from various standard types of power amplifier tubes connected singly, in parallel, or in push-pull, when the maximum allowable signal-voltage input (see Fig. 214) is applied to the tube or "combination" in each case

ing, (about equal to the grid-bias voltage), is applied. Separate values are given for single output tubes, for 2 tubes in parallel, and for two tubes in push-pull. In each case it is assumed that the maximum plate and grid voltages specified for the tube in the table of Fig. 214 are applied to the tubes.

It must be understood that the power output requirement is not the only consideration in the selection of a power amplifier tube in any specific case. The "power sensitivity" i.e., the measure of the input signal voltage required to produce a given power output is very important. Thus, a '47 type pentode will deliver more undistorted power output for a given signal voltage applied to the grid, than say a '45 type tube, i.e., its "power sensitivity" is higher. Therefore it is usually more satisfactory than a '45 type tube, because for a given power output, less amplification of the signal in the preceeding stages is required. This consideration has made the pentode type of tube very important as a power amplifier.

451. Tone control: As radio receivers designed for the reproduction of speech and musical programs must operate under varied acoustic conditions in the many types of rooms in which they are used, and must also please the individual acoustic tastes and preferences of the listeners, the incorporation of a tone control in the audio amplifier has become quite common. Many people prefer reproduction with the bass over-accentuated and the high notes suppressed, others prefer the bass reduced and the high notes brought out, so that the speech sounds such as "s", "sh", "z", etc., are reproduced clearly and sharply. Others may want the audio system to amplify and reproduce equally, the entire range of audio-fre-

quencies concerned in the reproduction of speech and music, with a suitable control provided for either suppressing or over-accentuating either the bass or the high-note range for certain types of speech or music, if they so desire. The latter form of tone control is possibly the ideal type.

Many tone control arrangements consist of a simple high-pass or low-pass filter, (see Articles 180 and 185), which act to reduce the amplification of the high audio frequencies. This suppression of the high notes produces the effect of making the speech or music sound low-pitched. Thus a deep note effect is produced without actually increasing the amplification of the low frequencies. However, this form of apparent low-note boosting does not produce really natural reproduction, for since the high frequencies are cut off, the sound loses its brilliance and crispness. This is especially true for many of the speech sounds. The possible types of tone control systems are very numerous. The circuit of a typical simple tone control of this kind which has been used extensively on account of its simplicity is shown at (A) of Fig. 337. This consists of a .002 mf. fixed condenser in series with a variable non-inductive resistor of 500,000 ohms maximum value. At (A) this control is shown connected in the plate circuit of the detector tube. At (B) it is connected across the secondary of the input transformer of the push-pull output stage. In either case, the effect is to by-pass the high frequencies by means of the condenser, the adjustable resistor in series determining the amount of by-passing

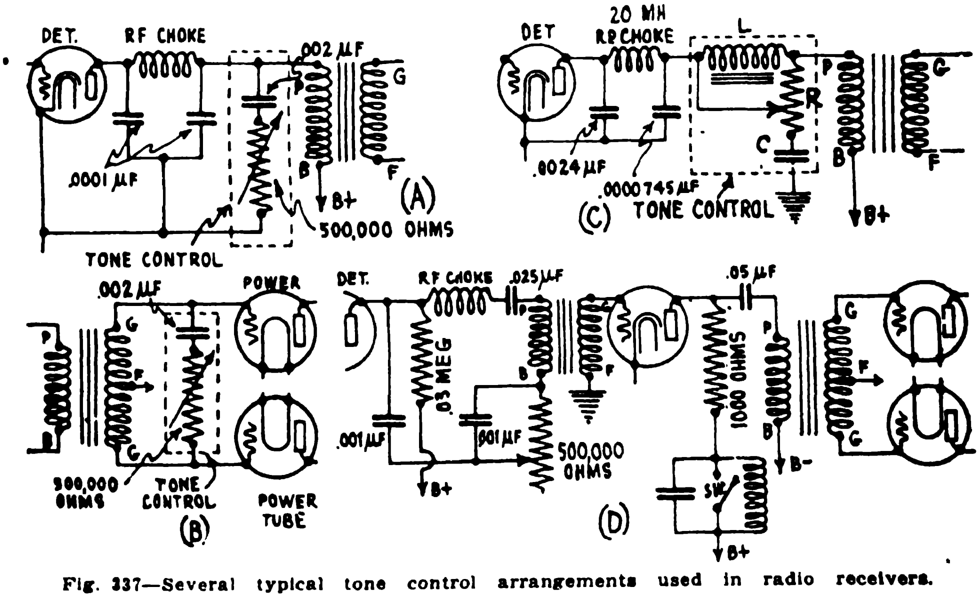


Fig. 337—Several typical tone control arrangements used in radio receivers.

which takes place through the circuit. The less the resistance in the circuit, the greater the by-passing effect and the lower the tone seems. The condenser by-passes the high frequencies only because its reactance de-

creases as the frequency increases. At (C) a very satisfactory tone control, also of the "suppressor type," is shown. This consists of an inductance L, of about 2 henries and 1300 ohms; a potentiometer R, of 40,000 ohms; and a condenser C, of .025 to .05 mf. depending on the audio characteristics of the receiver. The advantage of this circuit is that either the low or the high frequencies may be suppressed. It is usually connected in the detector plate circuit. As the arm of the potentiometer is moved toward the condenser terminal, the resistance of the condenser by-pass path is reduced and the high frequencies are by-passed, resulting in a deep tone. As the arm is moved toward the choke terminal, the condenser by-passing is reduced and the resistance of the shunt path across the choke decreases. This reduces the amplification of the low frequencies.

The tone controls just described are typical of the "frequency suppressing" or "de-amplifying" type. The audio amplifier has a certain a-f response, and the tone control reduces the amplification of the low frequencies or the high frequencies to below the normal value. In order to bring up the volume, it is necessary to manipulate the volume control whenever the tone control has been adjusted. No actual boosting of the amplification at any frequency can be produced by this form of tone control.

A form of tone control which actually enables the operator to either increase or decrease the amplification of the low or high audio frequencies if desired, is shown at (D). This is particularly adjusted to the resonated primary arrangement in the "Clough coupling" system as shown.

Varying the value of the 500,000 ohm resistor across the .001 mf. condenser varies the current flowing in the resonated primary circuit and therefore varies by as much as 15 decibels, the amplification of the lower audio frequencies below 100 cycles to which the primary is resonated. The amplification of the high audio frequencies can be either lowered or raised by means of the switch. In the plate circuit of the first a-f tube, is included a tuned circuit consisting of a capacity and inductance resonated at the higher audio frequencies to increase the impedance of this circuit at the higher frequency. This results in a very considerable boost of the order of about 22 db. at the higher audio frequencies in the neighborhood of 4,000 cycles. A switch is seen shunting this tuned circuit, which, when closed, throws it completely out of circuit and results in weakening of the higher audio frequencies. This is desirable in locations showing a very high noise level, in the reception of very weak stations, or where the personal taste of the user favors an accentuated bass response for certain music. This system is shown connected in a complete superheterodyne receiver circuit in Fig. 283.

Other systems of tone control wherein the amplification at either the high or low audio frequencies may be either increased or decreased have been developed, but many of them are too costly and complicated for general use in radio receivers, although they are employed in amplifiers used for public address and sound picture work. They usually provide for a series of controls which enable the operator to accentuate or attenuate any particular frequency or any particular groups of frequencies which he may desire. Thus, it is possible with an amplifier so designed, to not only compensate for losses in recording and reproduction, but also to attentuate those particular frequencies which are emphasized because of resonance in the electrical or mechanical network, or by the particular physical conditions existing in the place where the reproduction takes place.

REVIEW QUESTIONS

1. What is meant by the term "audio frequency"? What is a-f amplification?
2. At what point in a radio receiver is a-f amplification used? Why? What does it accomplish?
3. What are the practical advantages and disadvantages of doing all of the amplifying of the radio signal voltages in an r-f amplifier ahead of the detector?
4. What advantages and disadvantages does audio amplification following the detector present?
5. Draw a simple block-diagram and explain the various changes which an incoming modulated r-f signal voltage undergoes as it proceeds through the t-r-f amplifier, detector, audio amplifier, and loud speaker.
6. Why has the use of power detectors resulted in a change in the ratio of r-f (or i-f) amplification to a-f amplification employed in receivers, so that most of the amplifying is now being done in the r-f (or i-f) amplifier?
7. Name two practical limits to the amount of r-f amplification that can be used satisfactorily in a practical radio receiver?
8. Modern broadcasting stations are equipped to transmit all sound frequencies up to 8,000 or 10,000 cycles. Why do they actually transmit only up to about 5,000 cycles?
9. In order to obtain true reproduction of the sound programs, what must the entire radio receiver equipment considered as a whole, accomplish?
10. State some of the important characteristics of the human ear, as regards the power in sounds of equal loudness but different frequencies; and as regards the effect on the intelligibility if either the low frequencies up to 1,000 cycles, or the high frequencies above 3,000 cycles, are eliminated from speech sounds.
11. What is meant by "masking" of the high notes? What causes it?
12. What frequency characteristic should the audio amplifier and loud speaker in a receiver have, if the sideband frequencies have been suppressed in the r-f amplifier by too-sharp tuning? Explain and show by means of the frequency-response curves.
13. What improvement would be noticed in the reproduction of broadcasted musical programs if all sound frequencies up to 10,000 cycles were transmitted and reproduced faithfully instead of the present 5,000 cycle upper limit?
14. Define the "decibel". Of what practical importance is the decibel system of comparing power ratios?
15. A loud speaker having an efficiency of 10 per cent (only 10 per cent of the electrical power put into it appears as useful sound

power), is operated by an audio amplifier feeding 1.5 watts to it. The sound is to be made twice as loud. How much power will the amplifier have to deliver to the speaker for this condition?

16. What is the difference in voltage amplification, expressed in decibels, between an amplifier giving a voltage amplification of 400 and one giving an amplification of 800?
17. A certain amplifier is capable of outputting a maximum undistorted power of 1.5 watts. How much louder will be the sound if the output is raised to 5 watts by the use of larger tubes and more amplification? Will this increase in power be worth while?
18. Why should audio-frequency response curves be plotted to logarithmic scales instead of to ordinary uniform or equally-divided scales?
19. The plate resistance of a '27 type amplifier tube is, say 10,000 ohms. The inductance of the primary of the a-f transformer which is connected after it, is 50 henries, and it has a turns-ratio of 3 to 1. What is the amplification produced by this stage at 60, 100, 1,000 and 10,000 cycles (neglecting the ohmic resistance of the primary). Draw a graph showing the frequency response, with amplification plotted against frequency. Repeat this for a primary inductance of 200 henries. What is the advantage of using the primary of larger inductance?
20. What frequency range should an a-f amplifier be capable of amplifying uniformly for ordinary sound programs?
21. What three main methods of coupling may be employed between the tubes in a-f amplifiers?
22. Describe the construction of a typical a-f transformer? Why is the core *laminated*? What is the advantage of using a steel core instead of an air core?
23. Explain the action of an a-f transformer in an amplifier stage. Why is it desirable to have a high primary impedance, and a low distributed capacity in the windings?
24. Why is it common practice to use a low-ratio a-f transformer following a detector tube?
25. How does the use of a core of large cross-section area reduce the magnetic saturation effect in an a-f transformer? By what special circuit arrangement may this magnetic saturation effect be eliminated?
26. Explain how resonance is obtained in the Clough audio system and show why this resonance increases the amplification obtained at the resonance frequency. What are the advantages of this method?
27. Draw a circuit diagram of a typical complete battery-operated receiver employing two stages of tuned r-f amplification, grid-bias detector and two stages of transformer-coupled a-f amplification.

28. Explain why an a-f amplifying stage employing a transformer of low turns-ratio may sometimes produce more amplification than one using a cheaper type of transformer of high turns-ratio.
29. Explain the action of the resistance-coupled a-f amplifier, bringing out the effects produced by increasing or decreasing the values of the plate resistor, leak resistor and blocking condenser.
30. What limits the value of the resistance which can be employed in the plate circuit in a resistance coupled amplifier?
31. What particular advantage does resistance-coupling following a power detector tube have?
32. Explain the causes of "motorboating" in an amplifier. Show how this may be eliminated.
33. Draw a circuit diagram, and explain the operation of the impedance-coupled type of a-f amplifier. What advantage does this possess over the resistance-coupled type?
34. What is the advantage of the autoformer impedance-coupled amplifier over the ordinary impedance-coupled type?
35. Explain the operation of a 2-tube Loftin-White a-f amplifier, showing how the various plate and grid bias voltages are obtained, and how the hum voltage is neutralized. What are the advantages of this system over the ordinary resistance-capacity coupled amplifier?
36. What are the particular characteristics desirable in an interstage amplifier tube; in a power amplifier tube? What special features in the construction of power amplifier tubes are responsible for these characteristics?
37. A '45 type power amplifier tube is to feed its electrical output to a loud speaker connected in its plate circuit. If the a-c plate resistance of the tube is 1750 ohms, what must be the impedance of the speaker in order that *maximum power* be delivered to it, for a given signal voltage? How much power will this be if mu=3.5, and the peak signal voltage is 30 volts?
38. What must be the speaker impedance in problem 37, if the maximum *undistorted* power output of the tube, for this signal voltage, is to be put directly into the speaker. What would this output be?
39. Assume the speaker in problem 38 to have an impedance of 15 ohms. What must be the primary impedance and turns-ratio of an impedance-adjusting coupling transformer to couple it to the tube, if the maximum *undistorted* power output for this signal voltage is to be obtained?
40. Draw a circuit diagram of, and describe the operation of a choke-condenser type of output coupler for coupling a magnetic type cone speaker to a power tube. Why is this needed? Why should the speaker circuit be returned directly to the filament circuit?

41. Explain the difference between "frequency distortion" and wave-form distortion of an a-f amplifier. Explain with the aid of diagrams, the various operating conditions which may cause each.
42. Explain the action of the push-pull amplifier in detail. Explain how it eliminates the "second harmonic" distortion.
43. List three advantages of the push-pull connection over the single tube, and parallel connections, and explain.
44. A single '45 type tube operated at maximum rated plate voltage is to be used as a power output tube. (a) What maximum peak value of signal voltage may be applied to it; (b) What maximum undistorted power may be obtained from it when this signal voltage is applied; (c) What value of load impedance is required for this condition? (Use chart of Fig. 214.)
45. The amplifier stage in question 44 is replaced by a push-pull stage using '45 type tubes. (a) What is the value of the undistorted power output which will now be obtained if the same signal voltage as specified in question 44 is applied to *each* tube; (b) what value of load impedance is required for this? Compare your results with those found in question 44.
46. An output stage for an a-c electric radio receiver is to be designed. The peak value of the signal voltage applied across the primary of the 3 to 1 a-f transformer which couples this stage to the preceeding amplifier tube is 15 volts. What type of output stage and tubes would you employ? What undistorted power output would be supplied to the load when this signal was applied?
47 The push-pull output stage of a public-address amplifier must supply electrical power to operate four permanent-magnet magnetic, and three medium-size electro-dynamic loud speakers, at full volume. About how much power must it supply. What type of tubes and what connection would you employ in the output stage, single, parallel or push-pull? Why?
48. Draw the circuit diagram of a tone control which will reduce (a) the low frequency response; (b) the high frequency response; (c) either of the two. Explain how each affects the sound issuing from the loud speaker, as judged by the ear Which type is more desirable?
49. What features of the push-pull connection make it desirable for use in "power amplifiers"?
50. Draw a sketch showing the connections for a 2-stage dual push-pull amplifier What is the advantage of dual push-pull?

CHAPTER 25

LOUD SPEAKERS

TASK OF THE LOUD SPEAKER — PARTS OF A LOUD SPEAKER — CLASSIFICATION OF DRIVING UNITS — IRON DIAPHRAGM UNIT — BALANCED ARMATURE — INDUCTOR TYPE DRIVING UNIT — MOVING COIL DRIVING UNITS — THE MOVING COIL SPEAKER WITH ELECTROMAGNETIC FIELD — THE FIELD OR "POT" — THE "VOICE-COIL" AND INPUT TRANSFORMER — THE INPUT FILTER OR "EQUALIZER" — FIXED EDGE CONE DIAPHRAGM — FREE EDGE CONE DIAPHRAGM — CONSTRUCTION OF THE DIAPHRAGM — COMPLETE MOVING COIL SPEAKER — BAFFLE — PERMANENT MAGNET MOVING-COIL SPEAKERS — HORN SPEAKERS POSSIBLE SHAPES OF HORNS — EXPONENTIAL HORN — CUT-OFF FREQUENCY EXPONENTIAL HORN DESIGN — MATERIAL AND SHAPE OF HORN — HIGH FREQUENCY HORN SPEAKER — CONNECTING SEVERAL SPEAKERS — CONDENSER TYPE SPEAKER — DESIRABLE SPEAKER CHARACTERISTICS — COMBINING SPEAKER CHARACTERISTICS — REVIEW QUESTIONS.

452. Task of the loud speaker: We have advanced in our progressive study of radio receivers to the output circuit of the audio amplifier. Here we have the amplified audio-frequency voltage or current whose wave-form is continually changing in accordance with the wave-form of the sound acting on the microphone of the broadcasting station at the time. The next link in our radio receiving system is to convert the electrical power delivered by the power amplifier stage in the audio amplifier, into sound energy or waves of similar wave-form, which travel out to the ears of the listener and produce the sensation of sound in the brain, (see Fig. 300). We found during our study of the simple crystal-detector receiver system that earphones could be used for this purpose, but these are not satisfactory since they must be held close to the ears. Modern standards of home reception demand that the reproducer handle a sufficient amount of electrical energy to enable it to produce sound waves sufficiently intense to be easily heard and distinguished anywhere in a room of at least ordinary size. For public-address and sound-picture work, the volume of sound produced must be sufficient to be heard by large assembled audiences everywhere in large halls, auditoriums, theatres, etc. This is accomplished by the *loud speaker* or *reproducer*. The loud speaker really converts the electrical energy which is supplied to it, into sound waves, or sound energy. For this reason it is sometimes called an *electro-acoustic transducer*. Before proceeding with the study of the various

types it would be well to understand just what the requirements for a satisfactory loud speaker are.

The loud speaker should be reasonably free from wave-form distortion, i.e., at every instant it should produce a wave of sound pressure exactly corresponding to the wave-form of the electrical voltage impressed on it at that instant. It should also be reasonably free from frequency-distortion, which means that it must respond fairly uniformly to all audio frequencies which may be applied to it. Another requirement is that a loud speaker should have a linear response with respect to the strength of the signal-voltage applied to it. This means that its sound output must be directly proportional to the electrical input, or in other words, it must be free from *volume distortion* over the volume range required. Of course it must also be able to stand the ordinary amount of abuse and misuse and should be economical in initial cost, maintenance and operation.

The question of the frequency-distortion of loud speakers is a rather flexible one, for, as we shall see later, it is possible to obtain very satisfactory overall results with a loud speaker whose frequency response is not uniform, simply by designing the audio amplifier system preceeding it, with a non-uniform frequency response which corrects that of the speaker. This is a common procedure in commercial receiver design.

The efficiency with which commercial forms of loud speakers convert the electrical energy supplied into sound energy is very low. Most of them have efficiencies of less than 5 per cent, the poorer grades having efficiencies of around 1 per cent. The best type in common use in sound-picture work has an efficiency of only about 30 per cent!

Many types of loud speakers, operating on a number of basically different principles, have been invented. The reaction between a coil and eddy currents set up in a disc; the electrostatic attraction or repulsion between two charged metal plates; thermal expansion and contraction of a wire with variation of current through the wire; the "talking" arc; the expansion and contraction of crystals under the influence of an alternating electric field; all these and many other schemes have been used with more or less success. Practically all commercial speakers now in use depend upon the variation in the pull of a fixed magnet (permanent or electro-magnet type) on an iron bar, armature, iron diaphragm, or a coil carrying a current. Present-day loud speakers are by no means perfect, but they are capable of very satisfactory results.

453. Parts of a loud speaker: Most loud speakers consist of two main parts. That which changes the varying audio-frequency voltage or currents into mechanical vibrations is called the *motor, driving unit,* or *receiver.* The other part, which acts in conjunction with the "driving unit" to produce the vibration of the air particles may be either a *flat surface,* a *conical surface,* or a *horn.* We will study the construction and operation of the various types of driving units first and will then proceed to a consideration of the commercial forms of loud speakers and see how these driving units are applied to change the electrical energy to sound energy. Since the electrostatic type of speaker does not have a separate and distinct driving unit, it will be considered separately, later.

454. Classification of driving units: Any device in which motion is produced when a varying electric current flows through it, constitutes the basis of a loud speaker driving unit. The object is to produce as large a movement of the diaphragm as possible, with the least amount

of variation of the current. Loud speaker driving units may be broadly classified into the following two types:

(a) *moving iron* type
(b) *moving coil* type.

In the *moving iron* type, the attraction between the pole pieces of a permanent magnet and a magnetic diaphragm, rod, or reed is made to vary in accordance with the variations of the signal current flowing through coils of wire. Moving iron type driving units may be further subdivided into "iron diaphragm" and "balanced armature" types. In the *moving coil* type, the mechanical forces and motion are developed by the interaction of the varying magnetic field produced by the flow of the signal current in a conductor, and that set up by the strong magnet provided. This may be either a permanent magnet or an electro-magnet. Loud speakers in which the moving iron type driving units are employed, are commonly called *magnetic speakers* and those with the moving coil type of driving unit are commonly called *dynamic* or *electro-dynamic* speakers. These names are unfortunate, because properly speaking, both types of speakers are "magnetic" in that the mechanical forces developed result from magnetic reactions. Also, properly speaking, all forms of loud speakers are "dynamic", because the motion is caused by a force. However, these popular terms are in common use and have become so firmly entrenched in the language of the radio industry that it is doubtful if they will ever be changed.

455. Iron diaphragm unit: The iron diaphragm type of loud speaker unit is of the "moving iron" type, and has the same general construction as the ordinary earphone described in Articles 250 and 251.

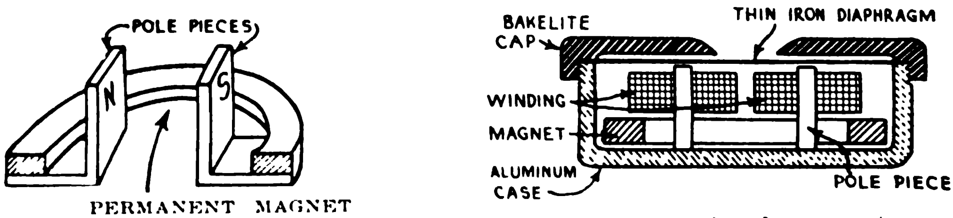


Fig 338—Iron diaphragm type of loud speaker unit The horseshoe shaped permanent magnet and soft iron pole pieces are shown at the left. A cross-section of the complete assembled unit is shown at the right. The windings are placed over the pole pieces

However, when built for use in a loud speaker, it is constructed with a larger magnet, coils and diaphragm since it must handle more energy than when used in earphones. Fig. 338 shows the arrangement of the U-shaped permanent magnet and soft iron pole pieces. A cross-section view of the entire unit assembled, is also shown. It operates in exactly the same way as described in Article 251, the movements of the diaphragm setting up the vibrations of the air particles directly.

A serious objection to this type of unit is that the diaphragm is under stress and is deflected by the magnetic field of the permanent magnet even when no signal is being received (see Fig. 181). This limits the amplitude of vibration of the dia-

phragm possible without rattling by striking against the pole pieces, when a strong signal is being received. If a unit of this type is to be sensitive, the air gap between the diaphragm and the pole pieces must be kept small so the field will be strong. This reduces the working amplitude of vibration possible without striking the pole pieces, and makes the unit unsuited for large volume. If the air-gap is made larger to permit of the large amplitudes of vibration necessary for large volume, the unit is not sensitive on weak signals. Also, the diaphragm being of iron, is comparatively stiff. This makes it difficult to build a unit of this type having good frequency-response. The diaphragm usually resonates at certain frequencies, causing abnormal response to notes of these frequencies. For these reasons, this type of loud speaker unit is no longer used much, although it was the most popular type in the early days of radio.

456. Balanced armature: The *balanced armature* driving unit was developed in an effort to eliminate the objectionable features of the iron diaphragm unit, as regards "rattling" or "chattering" on strong signals, and low sensitivity on weak signals. The "initial pull" or deflection caused

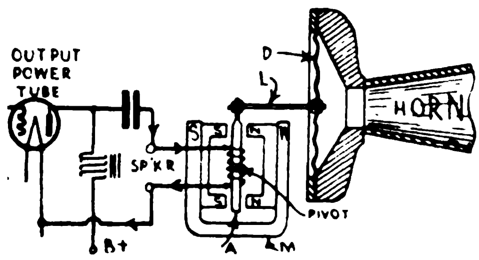


Fig 339—Balanced armature driving unit with its coil connected to the plate circuit of a power tube through a choke-condenser coupling The armature drives the diaphragm in the throat of a horn

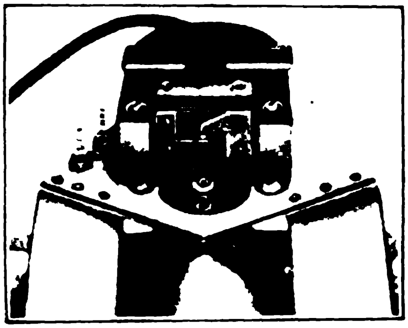


Fig 340—A balanced armature driving unit with its armature arranged to drive the paper cone in a moving-iron cone type loud speaker Notice the horseshoe shaped permanent magnet, and the pole pieces at the end, with the small rectangular iron-armature between

by the permanent magnet in the iron diaphragm type unit is eliminated by a clever construction which *balances* the initial pull of one pole against that of the other. Hence the name *balanced armature* unit.

Fig. 339 shows a diagrammatic sketch of a balanced armature type unit connected through an output filter to the output circuit of the power tube in the audio amplifier of a receiver. This particular unit is designed to vibrate the diaphragm D, in the throat of a horn speaker. A short, soft-iron bar, armature, or reed, A is pivoted at its center, so its ends are free to swing back and forth like a see-saw about this pivot. Each end of the armature moves between two pole pieces of the permanent magnet, and these are arranged with the relative magnetic polarity shown. Around the armature is a stationary coil consisting of several thousand turns of fine wire through which the signal current is sent. Enough clearance is provided between the armature and the inside of the coil so the motion of the armature is not restricted.

When no current flows through the coil, the armature takes a "center", or "balanced", position between the pole pieces, since the pulls of the pole pieces neutralize each other. Hence, the name "balanced armature unit". When the signal current flows through the coil, it magnetizes the soft iron armature rod. Suppose the direction of the current is such that the top end becomes a N pole and the bottom end becomes a S pole. Then the top end will be repelled by the N pole-pieces of the magnet and attracted by the S pole-piece. Therefore it would tend to move to the left. Since the bottom end is attracted by the N pole at the right, and repelled by the S pole at the left, it moves to the right. Hence, the two actions assist each other. The amount of deflection of the armature is nearly proportional to the strength of the signal current flowing through the coil, so it moves in accordance with the variations in the current. When an audio signal current flows through the coil, the armature vibrates back and forth very rapidly between the pole pieces. It may be fastened either directly as in Fig. 339, or by a simple lever system as at the left of Fig. 348, to either a flat diaphragm in the base of a horn, or a cone diaphragm, so as to impart its motion to the diaphragm in order to vibrate a larger volume of air and thus create a louder sound. As equal pulls are produced at each end of the armature, the motion is "balanced". The amplitude of vibration of the diaphragm may be increased and the pushing force decreased, or the motion may be decreased and the pushing force increased, by suitable mechanical lever linkages between the armature and the cone or diaphragm.

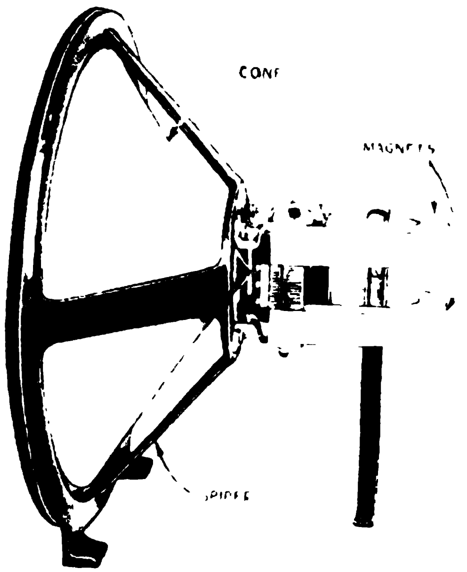
Units of this type made for use with long horns usually have a wide flat, thin armature, to secure a great driving force. The diaphragm can be made of a flat thin piece of mica or aluminum, for lightness. Fig. 340 shows a unit of this type which is used as the driving unit for a cone speaker diaphragm. Notice the pole pieces at the end of the permanent horseshoe magnet. Another unit of this type is shown in Fig. 51. It is important that an output coupler consisting of a choke coil and condenser as in Fig. 339, or an output transformer, (see Article 446), be used with units of this type to keep the direct plate current of the power tube out of the winding, and allow only the varying signal current to flow through.

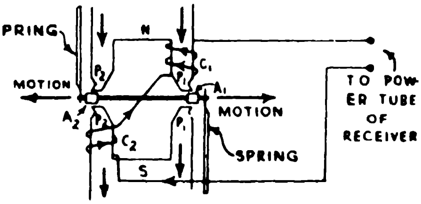
The balanced armature driving unit has been developed to a high degree of perfection and will give very good performance if it is operated properly with some regard for its limitations. It was the most popular type of unit for several years, and is especially useful in connection with battery-operated receivers. One of its serious limitations is that for good sensitivity, the air gap between the armature and pole pieces must be made very small to reduce the reluctance of the magnetic circuit and obtain a strong magnetic field. This is objectionable when receiving loud low notes, since the movement of the armature may be so great that its ends strike the pole-pieces, causing a rattling sound. If the air-gap is made large in order to provide for greater amplitude of vibration, the strength of the field decreases, with proportionate loss in sensitivity. If this is compensated for by increasing the number of turns on the coil, the high frequencies will not be reproduced, because of the increased distributed capacity of the coils causing a by-passing effect to the currents of these frequencies. However, for moderate amounts of volume, this type of unit is satisfactory especially when the cost is considered as a factor.

457. Inductor-type driving unit: The inductor driving unit is a moving iron type speaker of the balanced armature type in which the armature moves longitudinally between the pole pieces instead of cross-

wise. In this way the limitation due to the armature striking the pole pieces, on loud signals is overcome. This type of driving unit is often called an inductor dynamic unit. It uses two powerful U-shaped permanent magnets, (see Fig. 341), to supply the steady magnetic field. Instead of the usual moving coil or armature bar, the armature consists of two separate iron rods, A_1 and A_2, in Fig. 342, connected by tie rods as shown, each bar working between its respective pole faces.

The armature has a reciprocating motion instead of a swinging one. The coils C_1 and C_2 are connected in series and consist of several thousand turns of fine magnet wire wound on bobbins which are slipped over the pole legs. The action is as follows:





Left—Fig. 341—Complete inductor-type driving unit attached to the spider frame and paper cone diaphragm to form a complete speaker.

Right—Fig. 342—Cross-section view showing the relative positions of the pole tips, coils, armature, rod and springs in the inductor-type driving unit. The armature A1–A2 moves sidewise.

The armature assembly rides freely between the pole pieces P_1 and P_2. A signal current flowing through the winding in the direction indicated, will increase the flux (magnetic field) through the pole legs P_1 and decrease the flux through the pole legs P_2 (remembering that the magnetic lines of force of a magnet flow from the north pole across the air gap to the south pole as shown by the arrows). The flux, seeking the path of least reluctance, exerts a greater force on the armature bar A_1 than on bar A_2 since it is nearer to the pole piece, and the force on A_1 is greater than that on A_2, thus moving the armature to the left. On the reverse of the cycle the armature moves in the opposite direction in the same manner. The pole legs are cut to the shape indicated, to reduce the leakage flux and to bring the greatest flux density to the most desired point.

If the inside spacing between the armature bars is equal to the center spacing of the pole faces, the flux in the magnetic circuit P_1 A_1 P_1 varies 180° out of phase with the flux in the circuit P_2 A_2 P_2 as the armature is moved to its two extremes. This would give extreme sensitivity but there would then be no magnetic restoring force. If the armature bars are brought closer together, a distance corresponding to 18 electrical degrees, the resulting sensitivity is slightly decreased but there will be a restoring force set up, which will restore the armature to its initial position. The

total flux is greatest when the armature is in its "at rest" position and represents the magnetic restoring force, or, the "magnetic stiffness." This is the design used in practice. It is evident that any d-c component of current flowing through the windings would change the position of the armature by moving it to one side or the other, thus reducing its limit of motion in one direction. For this reason there must be no d-c flowing through the windings, thus making it necessary to use an output transformer or a choke and condenser. However, if the loud speaker is to be used with a push-pull amplifier, its winding may be used as an output choke and connected directly in the plate circuit of the push-pull tubes. A third lead may be taken from the windings at the point where the two coils are connected together and used as the mid-tap of the windings. This corresponds to the mid-tap on the primary of the usual push-pull output transformer. Doing away with the output transformer in this manner does away with its attendant losses and the gain is readily noticed by the ear.

It has been found that matching the impedance of the inductor dynamic to that of the amplifier with which it is to be used is of great importance. If the loud speaker has too high an impedance for that of the amplifier tubes with which it is used, the efficiency is lowered at the higher frequencies and increased at the lower frequencies. Since these loud speakers are made in several different models, each having a different impedance, and distinguished by a different color marking on the chassis, this feature affords the listener a chance to select a loud speaker which will give the balance of high and low frequencies which is most pleasing to him. A complete loud speaker of this type is shown in Fig. 341. The unit drives a cone-shaped paper diaphragm, both being supported by the rigid metal frame. Notice the two horseshoe-shaped permanent magnets.

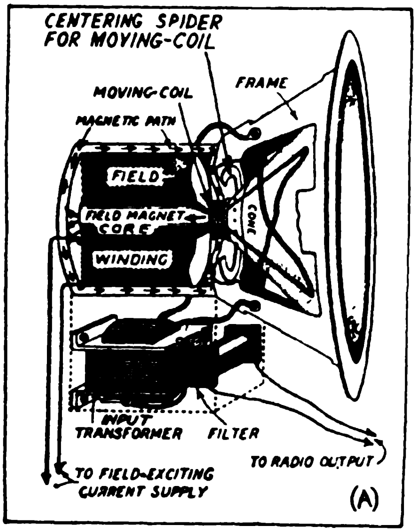
The advantages of this type of speaker are, that since the armature moves in a line parallel to the pole faces, it can be constructed to be sensitive due to the small air gap, and yet produce large amplitudes of vibration without striking the pole pieces. The armature moves over one-eighth inch when reproducing loud, low notes. Also the use of strong permanent magnets makes the unit cheap and simple and there is no possibility of objectionable hum being introduced by the speaker when used in electrically operated receivers, since it does not contain any electric light power supply, rectifiers, etc. It is particularly adapted for use with battery operated receivers for home use, in automobiles, etc.

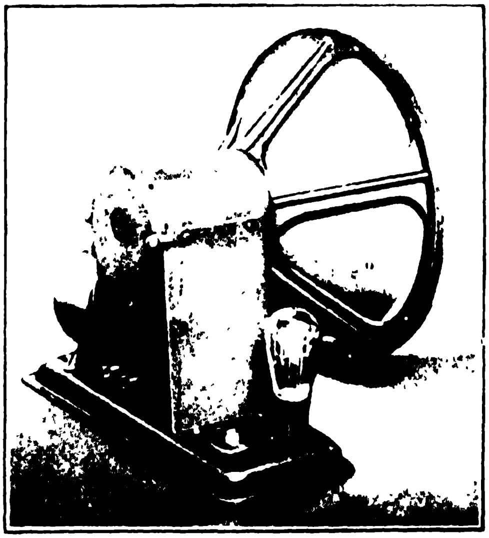
The name *inductor-dynamic* originates from the fact that the motion or force ("dynamic") is derived from a magnetic induction action ("inductor") similar to that in an a-c induction motor, where a rotor revolves under the influence of a changing magnetic field. Units of this type are usually used to drive 10 or 12 inch speaker cones for setting the air in vibration and producing sound waves.

458. Moving-coil driving units: In the moving-coil type of driving unit, a very small, exceedingly light cylindrical coil of wire (voice-coil) carrying the signal current, moves back and forth in the annular magnetic field between two concentric strong magnetic poles. The coil is attached (usually directly) to a paper cone, or a non-magnetic diaphragm when used with a horn. The magnet may be either a permanent

magnet or an electro-magnet. The latter type will be studied first, as it is the most popular.

459. The moving-coil speaker with electromagnet: The moving-coil type of speaker unit (commonly called the electro-dynamic speaker), differs from those already described, in that the audio-frequency signal current flows through a small exceedingly light, cylindrical coil of wire called the *moving-coil* or *voice-coil,* mounted so it "floats" in the intense radial magnetic field in the small circular gap between the central core and the end ring of a powerful electromagnet, as shown in Fig. 346A. The current flowing through the coil produces a magnetic field of its own. The action of the two fields produces a force which moves the coil along the axis of the core. Since the signal current varies in strength, the force acting on the voice-coil also varies accordingly, so it vibrates back and





Courtesy Jensen Radio Mfg. Co.

Fig 343—Left Cut-open view of an electro-dynamic type loud speaker having a moving coil driving a cone type diaphragm The construction of the field magnet winding, field core and outside shell are clearly shown
Right A typical auditorium type electro-dynamic speaker designed to handle large input power The rectifier tube in the foreground is for supplying the d-c field current from the a-c electric light socket

forth in the direction of the axis of the central circular core, the movement being proportional to the increase or decrease of the current at every instant. Since the coil moves along the axis of the core, it may vibrate over large distances without striking anything, hence it may be used for loud reproduction of even the lowest notes without danger of rattling due to striking pole-pieces, etc. This is one of the most important advantages of this form of driving unit. The relation of the various parts is shown at (A) of Fig. 343. This shows a section view of a moving coil unit with an electromagnet supplying the strong magnetic field. The moving-coil is attached directly to a cone-shaped paper diaphragm of the

free-edge type, as shown at Fig. 346A. A typical commercial electro-dynamic loud speaker of this type, suitable for use in large auditoriums, is also shown in Fig. 343. This will handle as much as 20 watts of electrical energy fed to it by a power amplifier. We will now proceed to study the design and construction of the various parts of a driving unit of this type. These are shown in Fig. 350.

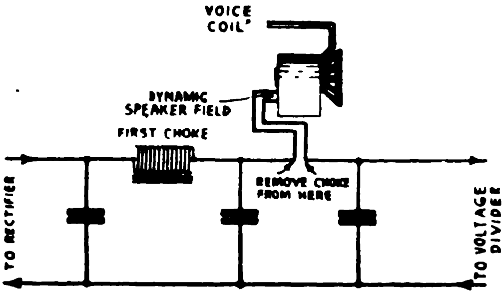
460. The field or "pot": The electromagnet which supplies the strong steady magnetic field in which the voice coil is suspended, is commonly called the *field magnet* or the *field pot.* The stronger the audio currents through the moving coil and the greater the value of the steady flux due to the field, the greater is the movement of the cone and therefore the louder is the sound produced. It is of advantage therefore to produce as high a flux-density as possible in the air-gap. Commercially, the loud speaker manufacturer designs the units for maximum flux density consistent with reasonable cost and a reasonable amount of power consumption from the source supplying the field power. In order to secure as strong a field as possible, the field winding is wound on the center core-leg and is surrounded by the magnetic steel shell which forms part of the magnetic circuit (see Fig. 343). This forms an iron-clad magnet. And since the lines of force have practically a complete path in the steel, a very strong field is produced for a given number of ampere-turns in the field winding.

Two general types of field magnet structure are to be found, cast and stamped. Cast steel or malleable iron is usually used with the cast design, while ingot or Swedish iron is used in many cases when the stamped design is used. Ingot iron is a better magnetic material than the cast product so that a lighter field assembly is permissible. Any material of a magnetic nature can be used with equal results if sufficient weight is used. In the case of cast iron, for instance, the total weight required would be so much greater that it is not economical The increased tendency toward the use of stamped field pots (see Fig. 350), is due to this higher efficiency and to the elimination of many machining operations necessary with the cast product

The field winding consists of a large number of turns of enameled copper wire wound to fill the space between the center core and the outside part of the field pot (see left of Fig. 343). About 800 ampere-turns are arbitrarily used in small speakers, and from 1,000 to 2,000 ampere-turns are used in the larger ones A greater magnetizing force is thus employed in the larger units. Electric power to energize the field winding may be obtained from a storage battery, from the filter system in a "B" power supply unit, or from the electric light socket.

When the field current is supplied from a 6 volt storage battery, the field coil is wound with rather thick wire (about No. 20 B. & S.), since it must have a low resistance in order that the 6 volts may force about 1 or 2 amperes through it. Most fields of this type are designed to operate at medium field strength direct from a 6 volt storage battery, or at increased strength from a 12 volt battery. A typical field winding of this type contains about 1600 turns of No. 20 wire, its resistance being 8.5 ohms. At 6 volts it takes 0.7 amp., and 4.2 watts of electrical energy are being used in it steadily merely to produce the intense magnetic field.

In most electrically operated receivers, the field winding of the electrodynamic speaker is used as a choke in the filter circuit of the "B" power supply device by connecting it in the filter as shown in Fig. 344. The steady direct "B" current furnished by the "B" power supply flows through this field winding and so energizes it. In this way the problem of field current supply is solved simply and the cost of a choke coil in the



Courtesy Best Mfg Co

Fig 344—Left Connection of the speaker field as a filter choke in the B power supply unit In this way the energizing field current is supplied and the field performs a very useful purpose besides
Right A typical dynamic speaker with a 2500 ohm field coil designed to be connected as a filter choke in the power supply unit of the radio receiver with which it is used. The input transformer is at the lower right

filter system is saved, since the field coil consisting of many turns of wire wound on a magnetic core has quite a high inductance, and acts as an excellent choke coil. It also saves the cost of a power transformer and rectifier which would otherwise be required for the speaker, as we shall see. In many cases the field coil of the speaker is the only choke used in the filter of the "B"-supply system. Several ways of connecting the field will be studied in detail later when "B"-supply systems are considered. As we shall see in Art. 510 the voltage drop across the speaker field may also be made to serve as a voltage-divider or as a source of grid-bias voltage in the receiver, thus saving the cost of the separate resistors which are ordinarily used for thus purpose.

It is evident that satisfactory results with this method of field supply can only be obtained when the proper value of current which is required to fully energize the field is sent through it. It may be necessary to connect a bleeder resistor across the line at some point following the speaker, in order to increase the current to the proper value required by the field. Fields designed to receive their energizing current in this way are made with various values of resistance and with various current requirements. Representative windings of this type are: 22,000 turns of No. 34 wire, resistance 2.500 ohms, operated on 110 volts, 44 milliamperes; 39,000 turns of No. 36 wire, resistance 7,500 ohms, 180 volts, 24 milliamperes. Other field resistances which are commonly employed are 650 ohms, 1,000, 1,200, 1,400, 1,600, 1,800, 2,000 2,250, 3,000 and 5,000. A speaker of this type is shown at the right of Fig. 344. Where a 110 volt or 220 volt d-c electric light line is available, the field winding may be energized by connecting it directly across this line, providing the field has the proper resistance and current rating.

When current from the 110 volt a-c electric light line is to be used to energize the speaker field, as in the case of public-address systems, outdoor announcing, small theatres, etc., some form of rectifier and filter must be employed, for if alternating current were sent through the field an alternating magnetic flux would be produced. This of itself would cause the voice-coil and the attached diaphragm to vibrate in accordance with these field variations, producing a loud, objectionable, low-pitched hum. The current supplied to the field must be absolutely uniform and smooth in order to create a field always in one direction, and unchanging in value. Two types of rectifiers are used for changing the a-c to d-c. One is the dry-plate copper-oxide or cupric-sulphide type (see Article 214) and the other is the common vacuum tube type.

When a dry-plate rectifier is employed, the 110 volt a-c line voltage is usually stepped down to about 12 volts at about ½ ampere by a step-down transformer (see (G) in Fig. 350). The secondary connects to the copper-oxide rectifier, and the rectified current flows through the speaker field, as shown at the left of Fig. 345. A speaker of this type is shown at the right of Fig. 346.

The current supplied by a rectifier of this type is a pulsating direct current with ripples of 120 cycles. It is evident that the magnetic field produced by this current will also fluctuate. Since the voice-coil is in the field of this flux, there will be a reaction between it and the varying magnetic flux and the coil will tend to move, its movements having the same frequency as that of the field current. If the diaphragm

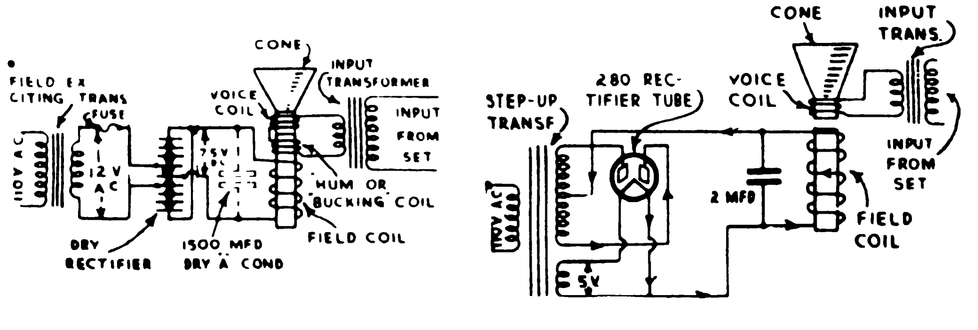
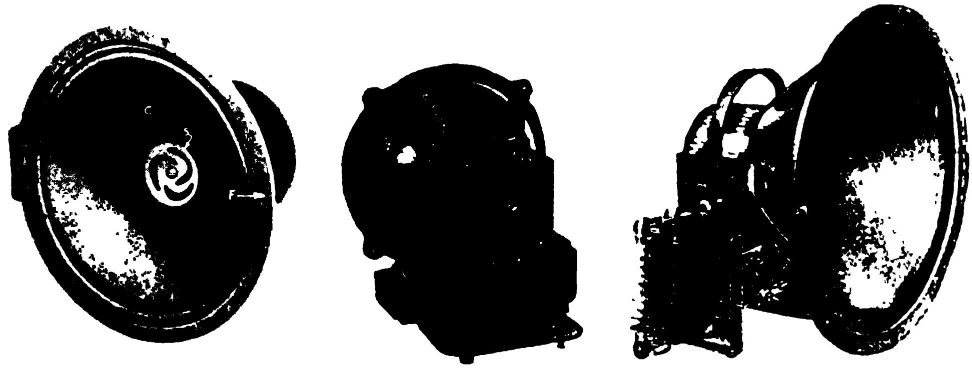


Fig. 345.—Left. How a dry-plate rectifier may be connected to the speaker field coil. Hum may be reduced by a dry electrolytic filter condenser or a "hum bucking" coil.
Right. How a vacuum tube rectifier and power transformer may be connected to change the a-c line current to smooth d-c for the field coil.

or cone moves, sound waves of this frequency are produced, and an audible hum results. The effect of this pulsating field current can be reduced greatly by a small stationary "*bucking*" or "*hum neutralizing*" coil which is wound around the pole-piece of the electro-magnet (see Fig. 345) and near the moving coil. It is connected in series with the moving coil and the secondary of the coupling transformer. As the bucking coil is also in the magnetic field, it has induced in it a hum-voltage corresponding in frequency so that of the pulsating field current. By making the bucking coil of the proper number of turns, and connecting it in the proper direction, its induced hum-voltage can be made equal and opposite to that induced directly into the moving coil by the pulsating magnetic flux of the *field coil*. Therefore, these two induced hum-voltages will balance each other and the hum is prevented, or at least greatly reduced.

One disadvantage of the bucking coil is that it also tends to reduce the response to signals around the hum-frequency of 60 and 120 cycles and therefore results in slightly weakened low-frequency response.

Obviously the bucking coil method of hum reduction is only practical when the coil can be included in the speaker at the time of manufacture. A very effective way of eliminating hum in any existing dynamic speaker which uses the low-voltage type of dry-rectifier, is shown at the left of Fig. 345. A dry "A" electrolytic low-voltage type filter-condenser of from 1,500 to 2,000 mfd. capacity is connected across the field coil. This large capacity serves to filter or smooth out all ripples in the field current. It should be remembered, however, that these condensers can be used only on speakers in which the low-voltage (about 15 volts) type of dry-rectifier is used, as they have a very low breakdown voltage.



Courtesy Jensen Radio Mfg Co *Courtesy Rola Co* *Courtesy Magnavox Co*

Fig 346—Left Front view of an electro-dynamic speaker showing felt ring F cone C, and spider S
Middle Electro-dynamic speaker with vacuum tube rectifier on the left The input transformer is directly under the tube
Right Electro-dynamic speaker with dry-plate rectifier mounted at its left

In connecting the dry "A" condenser across the circuit, it is important to make sure that the negative (black) lead of the condenser is connected to the negative side of the circuit, and that the positive (red) lead of the condenser is connected to the positive side of the circuit. The polarity of the circuit should be first determined with a voltmeter.

Another arangement has been developed in which the hum-voltage induced in the voice-coil is counteracted and balanced out by electrical means instead of magnetic. In practice, this takes the form of a small adjustable-resistance having a value of approximately 2 or 3 ohms and connected in series with the *field* winding The alternating current voltage drop across this resistance is applied in opposite phase relationship in series with the voice-coil circuit, causing the hum-voltage to be completely opposed, and resulting in zero hum. This device has the advantage that if the hum is introduced into the speaker from the radio set, it can also be balanced out, provided it is in phase, or in opposite phase, to the hum-current flowing in the movable-coil. Special high-voltage rectifier circuits using dry-plate rectifiers have also been devised, in which the rectifiers are connected directly to the line-circuit and have an output around 60 volts. The field winding of the speaker may have a resistance of 250 to 300 ohms in this case.

Instead of using a dry-plate type rectifier for rectifying the 110-volt alternating line current for field supply, a vacuum tube rectifier may be employed and connected as shown at the right of Fig. 345, provided the field power requirements are not too great. The power transformer at the left has a high-voltage secondary winding connected to the plates of the rectifier tube and a low-voltage winding for furnishing filament

current to it. The connection of the tube is the same as is employed in the usual "B" power supply unit used in radio receivers. The pulsating output current is filtered or smoothed out by one or more 2 mf. filter condensers in combination with the choking action of the high-inductance field côil itself, so as to eliminate any a-c hum which would be set up by the speaker due to the 120-cycle fluctuations in field current. This does away with the necessity for any "hum-bucking" coil. Also, the vacuum tube rectifier used is more reliable in operation than the dry-disc type of rectifier, and can very easily be replaced by the non-technical owner by simply plugging a new tube in the socket. The higher voltage used for the field makes filtering easy. Also since the current delivered to the field coil by the rectifier tube is in the order of 120 milliamperes, the field is wound with possibly 20,000 turns of fine wire of about No. 28 B. & S. A speaker of this type is shown at the right of Fig. 343. This is designed particularly for public-address work and can handle the output of amplifiers delivering as much as 20 watts of undistorted power.

When the rectifier in a dynamic speaker is nearing the end of its useful life, the volume of the music diminishes and the hum increases to a high level due to the imperfect rectification produced. When in this condition, the rectifier must be replaced. The density of the magnetic flux in the air gap in which the voice-coil is placed, is as high as 120,000 lines of force per square inch in some speakers, thus insuring great sensitivity and freedom from distortion, at great power.

461. The "voice-coil" and input transformer: A typical voice-coil is wound with about 90 turns of No. 32 enamelled wire in several layers on a light thin, tubular form usually of Bakelite. Since the end turns must always be taken off from the same end of the coil, an *even* number of layers of wire are generally used, usually two or four. The voice-coil form is rigidly fastened to the cone-shaped paper diaphragm. As the clearance between the sides of the voice-coil and the field core is only a few thousandths of an inch, the coil is usually kept permanently centered in a "floating position" by means of some sort of flexible "spider" arrangement which does not seriously interfere with the motion of the coil. The thin spider S shown in the speaker at the left of Fig. 346 is an example of this construction. Its center is bolted to the center of the center core leg, and its out side edge is fastened to the cone.

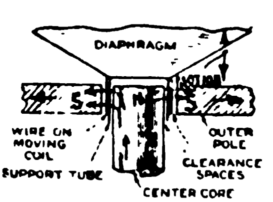


Fig 346A—How the voice coil is fastened to the cone and is suspended in the annular space between the center core and pole piece of a moving-coil type speaker

It is necessary that the voice-coil be free to move in and out of the gap at all times without touching any part of the field structure. In cases where the coil touches, a loud buzzing or scratching sound destroys the quality of the speaker. In this case it must be re-centered in the air gap. To do this, loosen the spider-fastening screws, or the center screw on the

spider if one is provided. Roll a piece of wrapping paper into the form of a small tube, such that it may be slipped between the center core-leg and the inside of the moving-coil form. This centers the coil. Now tighten the fastening screws and remove the paper. The cone should now be centered so it moves freely. In many cases, the cone on a well-designed speaker will move a total distance of three-sixteenths to three-eighths of an inch. This motion occurs when loud low-frequency notes are being reproduced, and causes a large variation in the air pressure at a given instant between the front and back of the cone.

As the voice coil contains a comparatively few numbers of turns, its inductance is small. Therefore it has a low impedance and acts practically like a pure resistance, its impedance increasing very little with increase in frequency over the audio range. This latter feature is very desirable since it is desired to have the speaker respond alike to all frequencies. In one commercial unit, the d-c resistance of the 92-turn moving coil is 4.3 ohms. The impedance of voice coils in moving coil speakers is considered as being about 10 ohms. However, there are a few makes of speakers with a voice coil consisting of a single turn of thin copper or duralumium ribbon having an impedance of less than .001 ohm. Since the impedance of the moving coil is much less than the plate resistance of any power amplifier tube it might be worked out of, in order to secure an efficient transfer of undistorted power from the plate circuit of the tube to the voice coil, an impedance-adjusting transformer of proper design must be used. This transformer is often called an *output transformer* when referring to the receiving set and an *input transformer* when referring to the speaker, (see Arts. 445 and 446).

Practically all electro-dynamic speakers contain an input transformer (the input transformer on the speaker at the right of Fig. 344 is clearly shown), designed with a high enough primary impedance to work efficiently out of standard types of 3-electrode tubes. When pentode tubes are used, a transformer having a special impedance ratio for them is necessary. The input transformer consists, like an audio transformer, of two coils of insulated wire wound on a laminated iron core. It is wound to match the plate impedance of the power tube to the lower impedance of the moving coil. As the impedance of a coil varies as the square of the number of turns, the transformer is designed so that the *square* of the ratio of the secondary turns to the primary turns is equal to the ratio of the voice-coil impedance to the desired primary impedance (see Art. 445). This may be illustrated by the following problem.

Problem: The 10 ohm voice coil of a moving coil speaker is to be efficiently coupled to the plate circuit of a '45 type power tube whose plate resistance is 1900 ohms. What must be the primary impedance and turns-ratio of the input transformer?

Solution: For maximum undistorted power output, the load impedance for a 3-electrode tube should be equal to about twice the plate resistance. Since the primary of the input transformer is the load impedance in this case, its impedance should be $1900 \times 2 = 3800$ ohms. Therefore the turns-ratio is found from

$$\left(\frac{T\ sec}{T\ prim}\right)^2 = \frac{10}{3{,}800}$$

$$\frac{T\ sec}{T\ prim} = \sqrt{\frac{10}{3{,}800}} = \frac{1}{19.5}\quad \text{Ans.}$$

The primary should have enough turns so as to have an impedance of 3800 ohms, and the secondary should have 1/19.5 as many turns as the primary.

When a push-pull output stage is used, it must be remembered that the output plate resistance is equal to twice that of one of the tubes. Thus, in this problem, if two 245 tubes in push-pull had been specified, the output plate resistance would be 2 × 1,900, or 3,800 ohms. In order to secure the maximum undistorted power output, the plate load would have to be 3,800 × 2, or 7,600 ohms. For two similar output tubes connected in parallel, the output plate resistance is equal to one-half that of a single tube.

The connection of the input transformer T, between the voice coil and power amplifier tube of a receiver is shown in Fig. 347. The proper input transformer is usually included with the dynamic speaker, so that when a dynamic speaker is connected to a receiver which has an output transformer or output filter in it, the output transformer or filter should be disconnected from the receiver first, and the dynamic speaker input terminals connected directly in the plate circuit of the power tube. Some manufacturers use a tapped primary on the input transformer so that proper matching can be obtained with any type of tube, for best performance. Because coupling ratios are not critical, it is fairly safe to say that any commercial dynamic loud speaker unit may be satisfactorily connected to the output of almost any receiver, unless pentode tubes are used. In cases where power pentode tubes are used, more efficient results can be obtained by using a special coupling transformer designed for them.

In receivers having push-pull output, satisfactory operation will be obtained with most commercial dynamic speakers by connecting them directly to the set output terminals (secondary terminals of push-pull output transformer in set). Some sets use a special push-pull output transformer having only a few secondary turns matched to operate directly into the voice coil winding of the conventional type of dynamic speaker, omitting the input transformer in the speaker. In this case, the push-pull output transformer secondary should be connected directly to the voice coil only, or else the regular dynamic speaker input terminals should be connected directly to the outer terminals of the primary of the set output transformer, ignoring the secondary terminals of this transformer entirely.

462. The input filter or "equalizer": Many makes of electrodynamic loud speakers have some form of filter or *equalizer* included as an integral part of them. These filters or equalizers cut off the reproduction above certain frequencies, or cause a power loss at some frequencies in order to reduce the abnormal loudness which would otherwise occur at those frequencies because of some "resonance condition," etc.

The most general type of filter consists of a simple "pi" low-pass filter consisting of a 100-200 millihenry inductance in series with the primary of the input transformer, and a 0.01 to .02 mfd. condenser across the line at each side of the inductance. This form of filter cuts off the frequencies above its natural resonant frequency of about 4,000 cycles and has practically no effect on the lower frequencies.

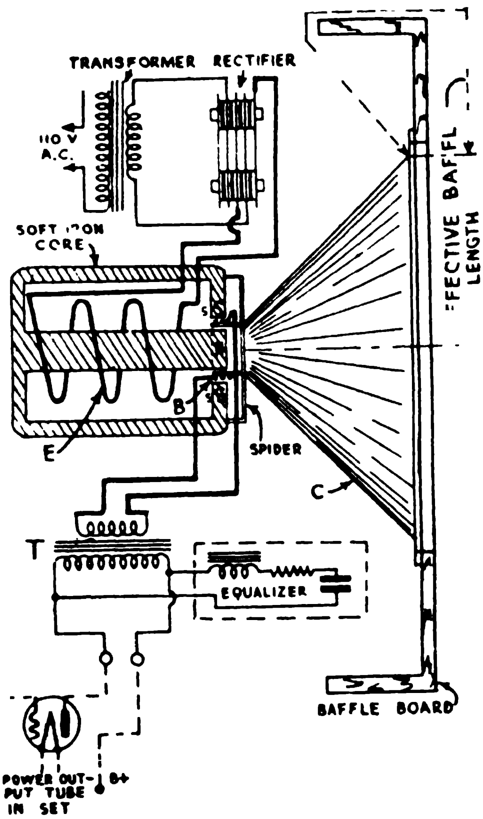


Fig 347—Electro-dynamic speaker with the voice-coil connected to the power amplifier tube through an input transformer T with an "equalizer." A hole is cut in the baffle board to allow the sound waves to get through

A 4000-cycle cut-off is very difficult to notice as far as speech is concerned but some of the brilliance is lost, especially for music.

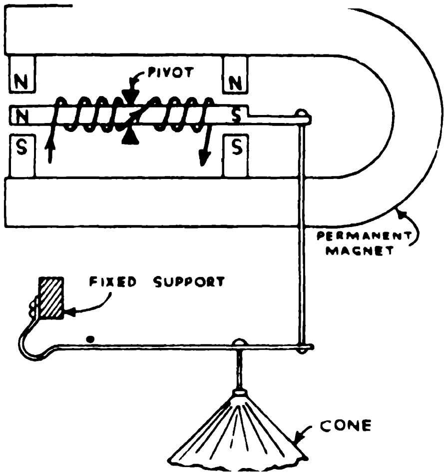
Another form of filter or equalizer, shown in the diagram of Fig. 347, consists of a resistance, inductance and capacitance in series, connected across the primary of the input transformer. At the resonant frequency of this circuit the attenuation is greatest. By proportionating the values in this equalizer, the "dip" may be made sharp or broad, and deep or shallow, to remove a resonant peak in the loud speaker output. This form of equalizer may be used to remove the peak where the wave-motion and plunger motion combine to cause an increased sound output.

463. Fixed-edge cone diaphragm: The vibrating armature of a moving-iron driving unit, or the voice-coil of a moving-coil unit do not set enough air in motion, to create loud enough sound waves. Therefore they are always used to drive some form of *sound radiator* which may take the form of a flat diaphragm operated at the neck of a horn, or a cone-shaped paper diaphragm. In the moving-iron type of driving unit, the armature usually drives the apex of the cone, through a simple lever system of the form shown at the left of Fig. 348.

Cone-shaped diaphragms may be of either of two types, the *fixed*-edge or the *free*-edge. In the fixed-edge cone, shown at the left of Fig. 349, the base of the cone A, is fastened to the base of a second cone B (or else to a frame), and the driving rod C, extends from the driving unit D, (rigidly fastened to the frame), to the apex of the cone. Thus the outside edge of each cone is not free to move independently. The cone speaker shown at the right of Fig. 348 is of this type. Well-designed and constructed speakers of this type have good frequency-response. In most of them, an adjustable apex set-screw or chuck arrangement is provided to compensate the small changes in the tension of the paper cone due to atmospheric changes. Moving-iron type cone speakers should always be

used with an output filter following the output power tube in the receiver.
At low frequencies, the cone acts as a sort of piston or plunger which pushes the air directly in front and in back of it. At the high frequencies, the inertia of the outside edges keeps them from vibrating while the center or apex region moves, thus tending to make the cone vibrate in sections instead of as a complete unit.

464. Free-edge diaphragm: In a free-edge cone, (shown at (A) of Fig. 349), the driving unit "A" drives the paper cone "B" whose base is free to move. The weight of the cone is usually supported by



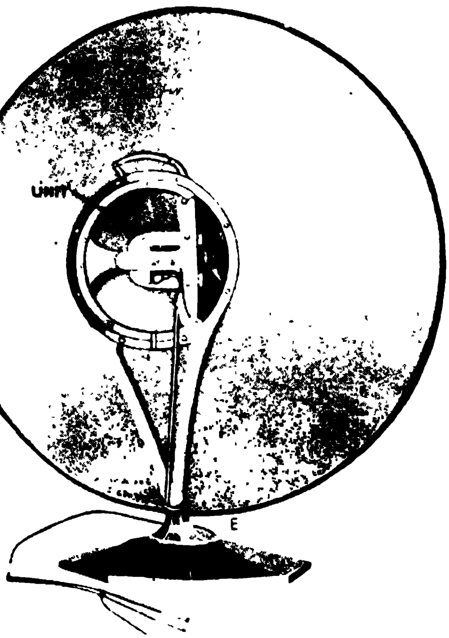


Fig 348 Left Lever system for balanced armature speaker unit driving a cone diaphragm
Right Rear view of Western Electric fixed-edge cone speaker with rear cover plate removed

mounting it on a rigid ring D by means of a thin flexible leather or chamois ring "C" which allows almost perfect freedom of movement of the cone. This type of speaker being unrestrained in its movement acts more nearly like a plunger or piston, and is capable of excellent reproduction. The cone is often corrugated or moulded in ridges in order to stiffen it and assure true plunger-like movement. Free-edge cones are used extensively. The speakers of Figs. 341, 343 and 346 all have free-edge cones. In each case, the cone is fastened to the metal supporting frame by means of a circular piece of thin, flexible chamois or goat skin.

465. Construction of the diaphragm: Cone shaped diaphragms are usually made of special grades of paper or other materials which do not absorb moisture readily and which have the most satisfactory combina-

tion of light weight, stiffness, freedom from rattling, etc. Heavy paper causes an energy loss due to the added weight and also reduces the high-frequency response due to the increased stiffness. The size of the cone also affects the frequency response. Special materials known under such trade names as Burtex, Tym-flex, etc. have been developed to supply the special properties required for the cones used in electro-dynamic speakers.

The cone diaphragms vary from about 6 inches in diameter for the small sizes, to 12 inches for the larger sizes used in auditoriums and public address work. Using a larger diaphragm results in a good low-frequency response, since for the same amplitude of motion there is, of course, a much greater amount of air set in motion. Conversely, for the same sound output the larger diaphragm does not have to move as far, which simplifies construction somewhat.

For low frequencies, 30 to 100 cycles per second, the amplitude of motion for good sound output is quite great. A motion of ¼ to ⅜ inch is not uncommon. Such great

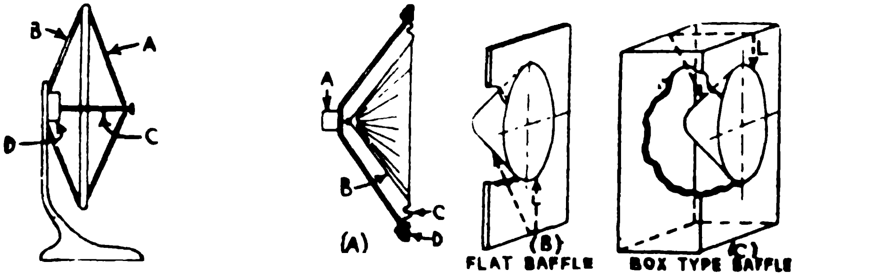
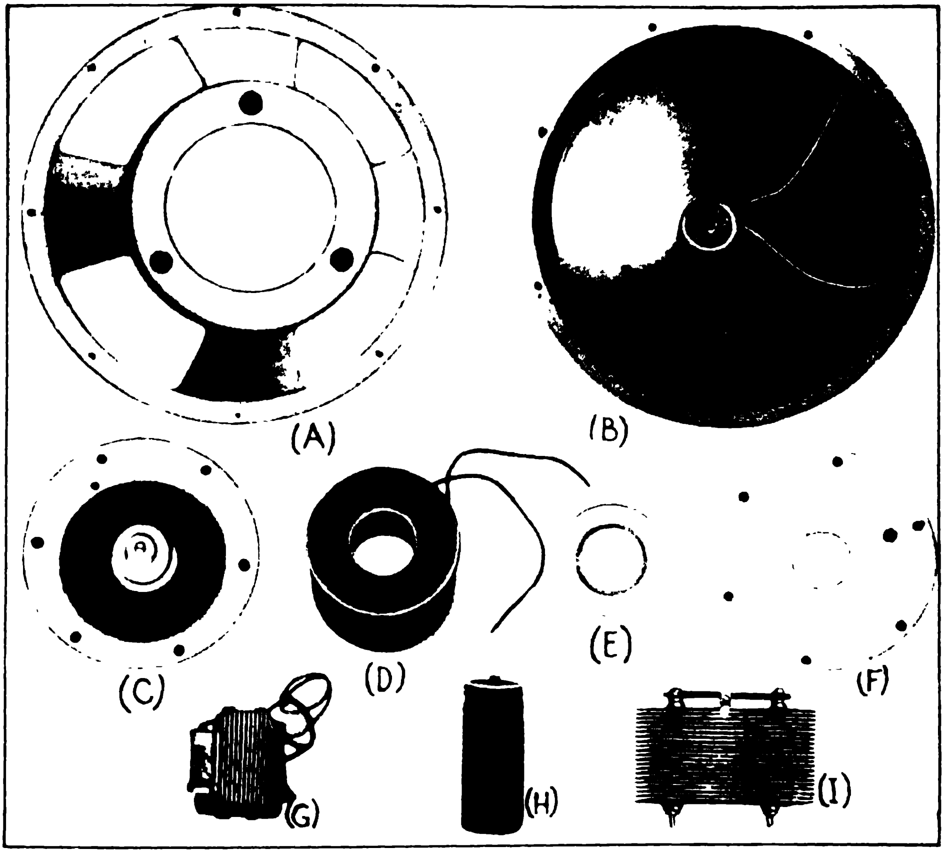


Fig 349—Left A fixed-edge cone speaker The edges are not free to move unrestrictedly Right (A), free-edge cone The edge is unrestricted, and may vibrate freely (B), A flat baffle (C), A box-type baffle

motion may cause crystallization of the springy centering-spider pieces, causing them to break in time. With the larger diaphragm, the motion is much less, so this tendency to break is greatly lessened.

466. Complete moving-coil speaker: The various main parts of a complete moving-coil type of speaker of modern design, with cone-shaped diaphragm is shown in Fig. 350. The metal cone bracket (A), supports the cone (B). The voice coil which is constructed very light, is fastened to the apex of the cone as shown at (B), its two ends connecting to the secondary of the input transformer. The outer edge of the diaphragm is fastened to a flexible cloth ring, and the latter is held by the spider frame. The stamped magnetic-steel field pot (C) has a center core over which the field winding is slipped. The copper shading ring (E) serves as an equalizer to reduce the response at a frequency range where a peak would otherwise occur—thus "equalizing" the response. The front plate (F) fastens to the top of the field pot, leaving a small annular air-gap around the central core-leg, in which the voice-coil moves up and down. The low voltage for the dry rectifier (I) is provided by the stepdown transformer (G), and an electrolytic condenser (H) is shunted across this to smooth out the current through the field winding and so eliminate the hum which would result if the field current were pulsating. The input transformer is not shown here.

467. Baffles: Before proceeding with the study of baffles, the reader is advised to study Fig. 2 which shows in detail how sound waves are produced by the vibrating cone of a loud speaker. A free-edge cone need not be large and unwieldy in order to reproduce the low-frequency notes, but it should be attached to a large baffle for this purpose. The



Courtesy Wright De-Coster Inc.

Fig. 350—The various parts which go to make up a typical, modern electro-dynamic cone type loud speaker. See Art. 466

baffle is necessary, because as shown in Fig. 2, both the front and back of a cone diaphragm set up air waves. Those of low frequency would alternately reinforce and neutralize each other, and seriously affect the volume of the low-frequency notes, if it were not for the baffle.

When the loud speaker is producing sound waves, the cone is in vibration, that is, first it moves forward in the direction shown by arrow A, in (A) of Fig. 351 and the next instant it moves in the direction of arrow B. The cone is shown attached to a dynamic speaker driving unit for simplicity. If the audio current flowing through the voice-coil has a frequency of say 100 cycles, then the cone moves in the direction A 100 times every second, and in the direction B 100 times every second. Each time it moves in direction A, it compresses the air in front of it. At the same instant, the air

in back of it is *rarefied* or *decompressed*, since the cone on moving forward has left more space behind for the air to fill. These differences in air pressure (more pressure in front and less pressure in the rear), immediately tend to equalize each other; the crowded air particles comprising the compression in front, immediately tend to move around the edge of the cone to the rear where there is a rarefaction

But sound waves are caused by movements of air due to tiny air pressures. If these pressures are allowed to neutralize each other, there will be no movement of air out directly from the front or the back of the speaker toward C or D, and hence no sound will be produced. If they partially equalize each other, very little sound will be produced. Consequently, something must be done to prevent the compressions produced at the front of the cone, from travelling around the edge from the front to the back *in time to equalize the corresponding rarefactions being produced at the same instant at the back*, (or vice versa).

This is accomplished by placing a baffle around the cone, taking either of the forms shown at (B) and (C) of Fig. 349. The air vibrations must now take the long path L around the baffle in order to get from one side of the cone to the other. By making this path long enough, the compressions cannot get from the front to the back of the cone(or vice versa) in time to equalize the corresponding rarefactions, as will now be explained.

It must be remembered that the current flowing through the voice coil is an alternating current (in the case of a speaker coil connected directly in the plate circuit of an output tube without coupling transformer, the current is a pulsating direct current, but the same reasoning also applies to this case). This alternating current may be represented by the familiar form shown at (B) of Fig 351, although the wave-form of actual voice currents is much more complicated than this, as shown at B of Fig. 171. Since the movement of the cone follows the variations in the current, the air pressure variations will follow the same wave-form In terms of air pressure in front of the cone, we can decide that from 1 to 2, the pressure is increasing above normal value, from 2 to 3, it is gradually decreasing to normal, from 3 to 4, it is decreasing below normal (a rarefaction); and from 4 to 5 it is gradually increasing to normal. The air pressure in front of the cone therefore, goes through four distinct changes during one complete cycle (one forward and backward movement of the cone) If the current has a frequency of say 100 cycles, there would be four times 100, or 400 changes in pressure per second. Sound waves travel about 1130 feet per second Therefore, in the case of a 100 cycle note, during any one change in pressure (each of which takes place in one 400th of a second), the sound pressure wave will travel 1130 divided by 400, or 2.82 feet. Keep that in mind for a moment. Now if we allow the pressure wave from the front to go around directly to the back of the cone it will neutralize the rarefaction wave there. But if we make this pressure wave travel around a distance at least equal to 2.82 feet, it will take it at least one 400th of a second to get to the back of the cone. But we calculated that this is the time required for one change in pressure. Therefore, by the time the pressure wave from the front gets to the back, the cone has changed its direction of motion and the back is now producing a pressure wave, so that the two waves do not neutralize each other but actually reinforce each other, making the sound appear somewhat louder.

It is evident then that the purpose of the baffle is simply to *delay* the meeting of the front and back sound waves by artificially increasing the distance of the sound-wave-path from the front to the back of the cone. It is evident, that to fully reproduce any note, the shortest length of the sound-wave path from the front to the back of the cone (distance L in Fig. 349) must be made at least equal to the distance the sound travels during the time it takes to complete one quarter of a cycle of that note (see (B) of Fig. 351), or during the time it takes the cone to move from the center position to the extreme position in either direction. The distance in feet, which the sound travels during one complete cycle is defined as the *wavelength* of the sound and is equal to the velocity of sound (1130 feet per second) divided by the frequency in cycles per second. Therefore, the minimum length a baffle should be,

to permit full reproduction of any frequency, can be easily calculated by the simple rule, that the baffle length in feet is equal to one-quarter the wavelength of the note to be reproduced. That is,

$$\text{Baffle length} = \tfrac{1}{4}\text{ W. L.} = \tfrac{1}{4} \times \frac{1130}{\text{Frequency}} = \frac{282}{\text{Frequency}}$$

A baffle to permit full reproduction of tones as low as 30 cycles must be at least

$$\frac{282}{30} = 9.4 \text{ feet in effective length (L)}$$

Referring to Fig. 8, the frequency ranges of the various musical instruments may be seen, and the lowest note which any instrument can produce may be ascertained. To reproduce the lower notes with a free-edge type of cone speaker, a baffle must be used. The graph of Fig. 352 shows the minimum size of baffle required for complete reproduction of

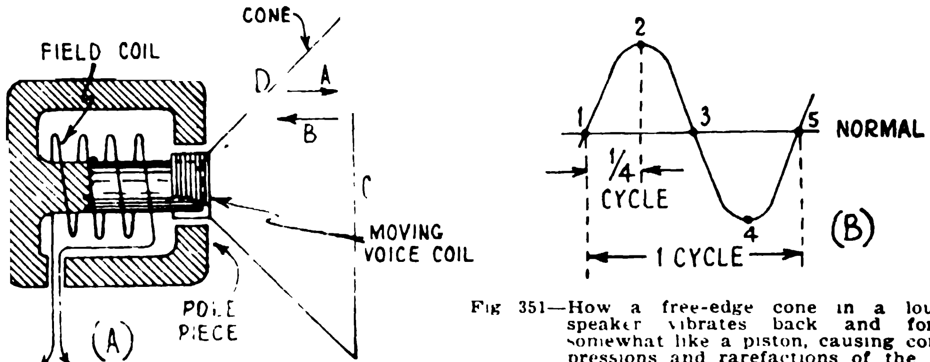


Fig 351—How a free-edge cone in a loud-speaker vibrates back and forth somewhat like a piston, causing compressions and rarefactions of the air particles in front and behind it

the various frequencies. These values were calculated by the above formula. The baffle size is given in inches, for convenience. This is obtained by multiplying the values obtained by the above formula by 12. At the top, the lowest frequencies of the various musical instruments are noted. This chart can be used to determine the size of baffle required for full reproduction of the lowest-frequency note of any musical instrument

A study of Fig. 352 shows that the required length of the baffle air path decreases as the frequency goes up. At 2000 cycles for example, the air path need be only 1.68 inches. Since the distance from the front to a point near the center of the back of an ordinary 10-inch diameter cone is about five inches, it follows that the cone itself is an effective baffle at the high frequencies Therefore the baffle is only important at the low frequencies and its size is determined by the *lowest* frequency to be reproduced.

It is difficult to define exactly what the baffle length is, since, strictly speaking, all parts of the cone are helping to produce sound. Some authorities define the baffle length as the distance from a point in the center of the front of the cone to a point in the center of the rear. This length would be slightly longer than that taken throughout this discussion. However, as the baffle lengths are usually worked out for low

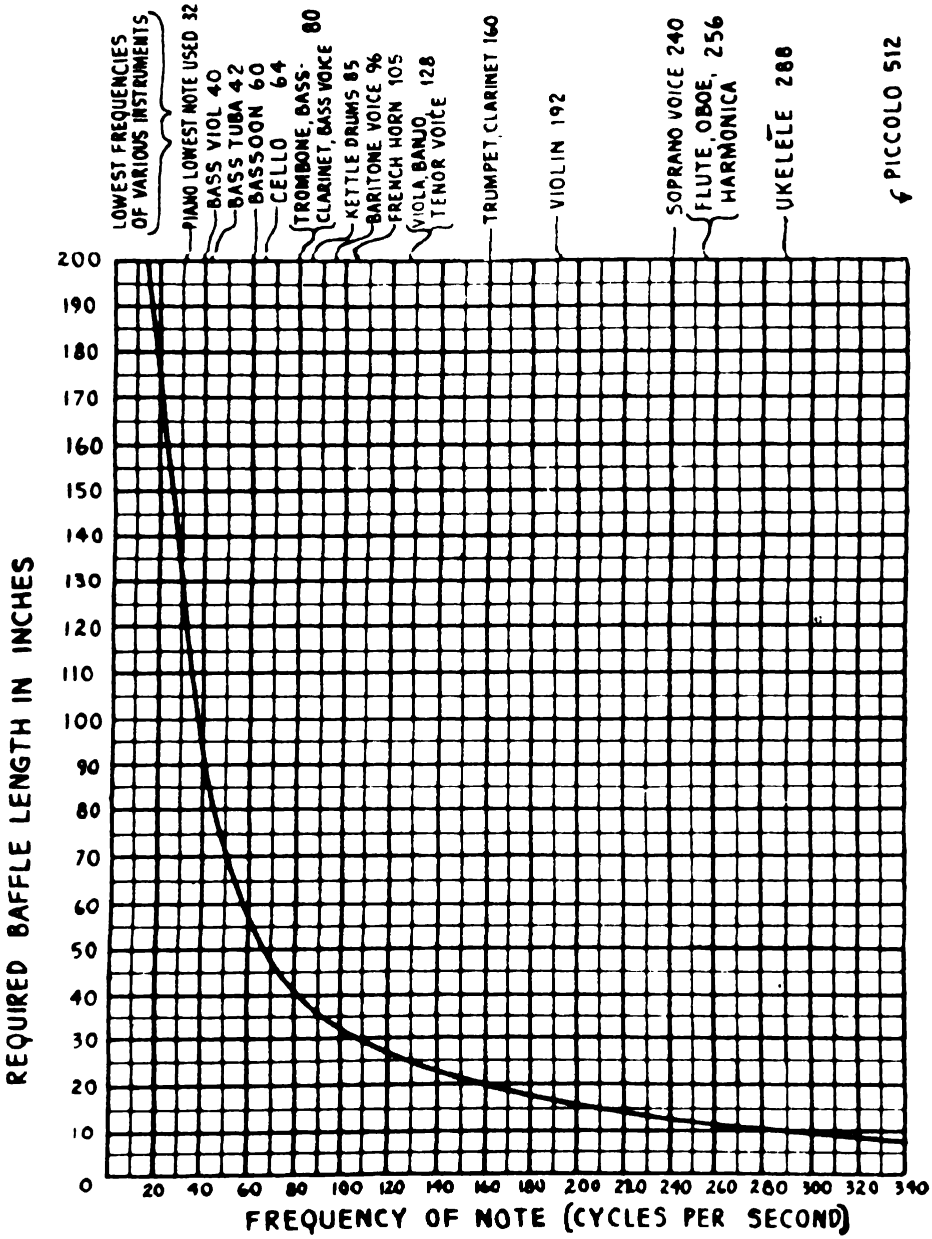


Fig 352—By means of this graph, the baffle length required for the full reproduction of low-frequency notes of various frequencies by a free edge cone, may quickly be determined

frequencies, and these lengths work out in most cases to 36 inches or more (see Fig. 352), a difference of an inch or two in considering the baffle length does not make much difference in the result.

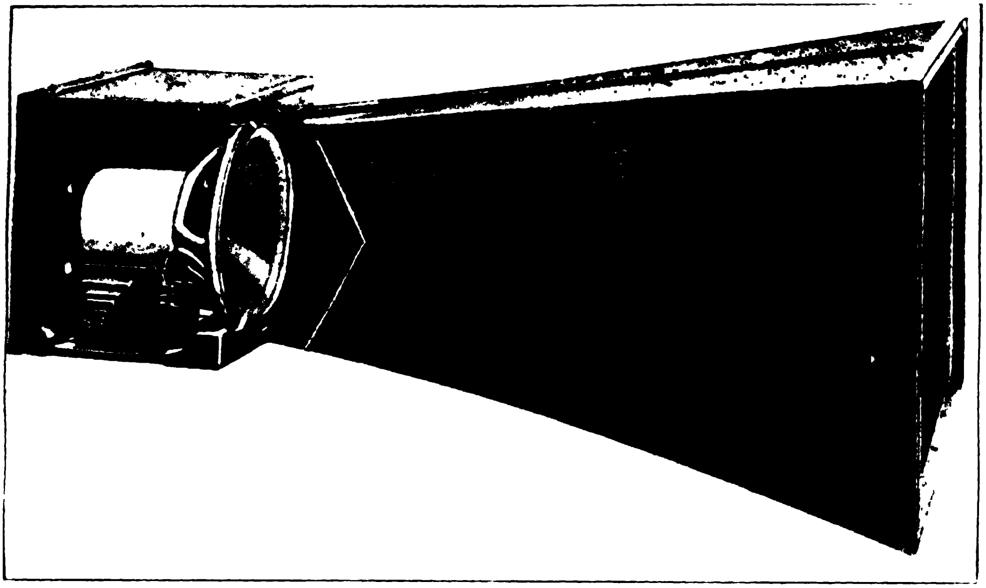
As it makes no difference how the length of air path for the baffle is obtained, baffles take many forms in actual practice. Flat baffles are probably the best types as they are not usually troubled by resonance effects, but their large size and ungainly appearance hardly make them suitable for use in homes. (B) of Fig. 349 shows a straight square baffle in position on a cone. In this type, the length of each side of the baffle is made equal to the length given in the chart of Fig. 352, since the total effective baffle length is about equal to twice the length of half a side.

(C) of Fig. 349 shows a box-shaped baffle which is more compact. This type is used extensively in homes because of its compactness and better appearance. The box type baffle is sometimes made up into artistic looking cabinets which blend in with the rest of the furniture in a room. The back of the box or cabinet-type baffle should be left open, to allow free circulation of the air. If it is closed up or restricted, resonance effects will be set up in the cabinet, resulting in better reproduction of some frequencies than others, and resulting in "barrel tone". The response of a cabinet-type speaker can often be improved by lining it with some non-resonant material such as thick felt, Celotex, etc. When a speaker is mounted in a console cabinet, the front, sides, top and bottom of the cabinet act as a box-type baffle, since sound waves issuing from the front of the speaker diaphragm must travel all the way around the sides of the cabinet to the back, and then forward inside the cabinet to the rear of the cone, in order to cause any neutralizing action. As this distance is quite long in most cabinets, good baffling is secured. It is well to point out here however, that the speakers in midget-type receivers are unable to reproduce the low notes fully, on account of the insufficient baffling which the small midget cabinet presents. While many of them appear to have a deep tone, this is simply because of the fact that the high audio frequencies have purposely been suppressed by the particular circuit design employed.

When a dynamic unit is operated in the same cabinet with the radio receiver, the entire system may break into continuous oscillation due to the mechanical vibrations being set up in the elements of the detector tube by the sound vibrations. The remedy for this is to wrap the detector tube in thick felt, or weigh it down with a heavy metal cap to damp the vibrations. (The back of the cabinet should be left open, to reduce acoustic resonance effects in the cabinet itself.) When mounting a cone-type speaker on a baffleboard, the felt ring (see F in the speaker at the left of Fig. 346) on the front of the cone housing should be pressed evenly and tightly against the baffle. A hole equal to the inside diameter of the felt ring should be cut in the baffle of course. Fig. 353 shows a horn type of baffle attached to an electro-dynamic speaker with a cone diaphragm. The baffle is cut away to show the speaker inside. Baffles of this kind are used in auditoriums, theatres, and outdoor public-address work. They not only

act as baffles, but also make the speaker directional, so as to direct the sound waves to the audience. Notice that the top side is practically straight. This tends to keep the sound off the ceiling. The bottom flares down, and the sides flare out toward the opening. A unit of this kind will take care of a 400 seat house, if it is not over 25 or 30 feet wide. Otherwise two or more such units may be used.

It must be evident that baffles do not act as "sounding boards" as many people think. They are not supposed to vibrate or emit sound waves themselves at all, although sometimes baffle resonance effects are



Courtesy Wright De-Coster Inc

Fig 353—A dynamic speaker mounted in a 48-inch horn baffle for public-address and sound picture work It is 30x21½ inches at the opening Speakers of this type may be mounted outdoors if required

designed to accentuate the response of some frequencies which the speaker itself is deficient in. Baffleboards should be made rigid and usually of soft wood at least three-quarters of an inch thick. Baffleboards made of Celotex, at least one inch thick, are also very good, as this is a non-resonant material, but in some cases the absorption reduces the high-frequency response. For very low-frequency reproduction, the wall or ceiling of a room may be used as a baffle by cutting a circular hole in it large enough for the cone to fit through, but usually the volume of sound is reduced by this since the sound waves produced at the rear of the speaker are not heard at the front and vice versa.

If a baffle is made smaller than the size required to reproduce a certain frequency, it does not mean that this frequency will be completely suppressed—it simply means that notes of this frequency will be partially

suppressed, the extent of this suppression being determined by how much smaller the baffle is than the correct size. If notes below the actual "cut-off" frequency of the baffle are impressed on the loud speaker, the resulting tone is made up mostly of the higher harmonics of these notes. Thus, while a baffle may not be large enough to permit of reproduction of a 60 cycle note, it may be large enough to permit of reproduction of the second harmonic frequency of 120 cycles. Thus this note would be partially reproduced, but, of course, not in its true tone. This accounts for the partial low-note reproduction effect produced by speakers having small baffles. Of course, it is assumed that the receiving set passes the low frequency signals to the speaker driving unit, and that it is capable of operating the cone at these frequencies. For instance, it would be foolish to design a 56-inch baffle to permit reproduction of 60 cycle notes, if the set and speaker combination was unable to reproduce any frequencies below 200 cycles. In this case a 17 inch baffle would suffice, and the reproduction with it would be just as good on this particular set and speaker as it would with the 56 inch baffle. With ordinary receiving equipment it is not necessary to use baffles larger than about 48 inches, since these give a cut-off frequency of about 70 cycles. Very few medium-priced commercial receivers really produced sound waves of as low a frequency as this.

Magnetic speakers of the free-edge cone type are also ideally suited for mounting inside of a radio cabinet and are usually cheaper to construct than the fixed-edge type. The construction makes a short driving rod possible and this helps to reduce distortion. They provide practically uniform frequency-response over a wide band of frequencies.

468. Permanent-magnet moving-coil speakers: In some applications of loud speakers, the supply of current for the field coil of the electromagnet of the type of moving-coil speakers already described, is not readily and conveniently available. Instances of this occur in battery-operated receivers used in the home, in receivers used in automobiles and in hotel and apartment house centralized radio systems, etc. For cases of this kind, a special form of moving-coil speaker may be used. All of the advantages of the moving coil type speaker are retained, but a permanent magnet is used instead of the electromagnet. Several permanent magnet arrangements have been developed for such speakers, one of which is shown at (A) of Fig. 354. It consists of four outside arms having similar poles, which join a common flat pole-piece at the top. This forms one pole. The pole piece surrounds the central core-leg with a small air-gap in between, in which the moving coil is suspended as shown at (B). The central core-leg forms the other pole, and the flux in the air-gap is almost radial. The relation of the magnet, center core, pole piece and moving coil are shown in the sectional view at (B). Magnets for speakers of this type are usually made of steel containing about 9 to 15 per cent cobalt, (see Article 82). The object to be attained in the design is to produce a very strong permanent magnet having low magnetic leakage, and of reasonably small dimensions, at a reasonable price. The moving coil and cone design

are practically similar to those of the types of moving-coil speakers already described. While it is not possible to make these permanent magnets as strong as the électromagnets which are used on the ordinary moving-coil speakers, they are made strong enough to produce satisfactory

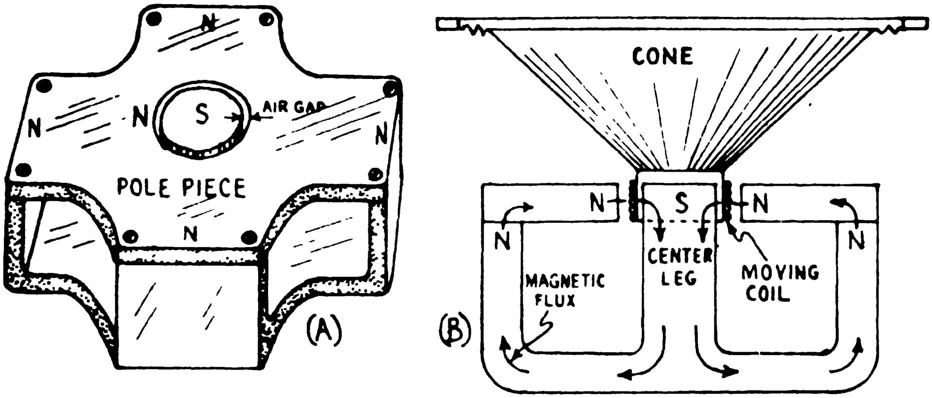


Fig 354—(A) Permanent magnet arrangement for moving-coil type speaker (B) Arrangement of permanent magnet, pole piece, moving-coil, and cone in a permanent magnet moving-coil speaker

speakers of this type. When the magnet in a speaker of this type becomes weak due to age, the volume decreases greatly and it must be remagnetized (see Article 93).

469. Cone and horn speakers: We have considered the use of a light-weight cone-shaped diaphragm operated by one of the forms of driving units which we have studied. The cone is used to set a large volume of air in motion. The use of a horn for this purpose has also been common for many years, but the proper design of the horn was neglected for some time. In the horn type of speaker, a diaphragm, usually of rather small size, may be driven by any one of the forms of driving units just described, and placed at the small end or *throat* of the horn. The function of the horn seems to be rather generally misunderstood Possibly the following simple experiment will illustrate the effect of the horn convincingly.

Experiment: Remove the driving unit from a horn speaker and connect it to a radio receiver or phonograph amplifier which is operating at medium volume. The diaphragm in the unit will vibrate in accordance with the signal impulses but since there is very little restraining force on it, it will rattle. Also since it is small, it does not act on very much air and consequently the sound produced is very weak.

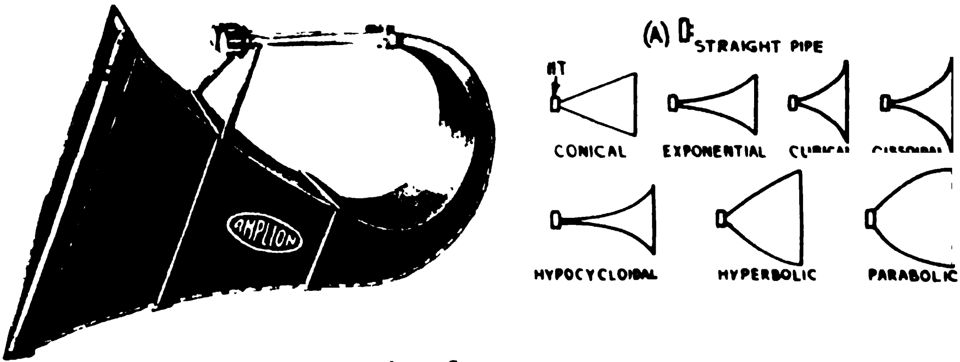
Now attach the horn to the unit. The rattling ceases because the diaphragm is now loaded since it pushes against the column of air in the horn, and the volume increases because a larger volume of air is being set in motion.

The horn adds nothing to the original intensity of the sound waves; all of the sound waves which are to come out of any kind of horn must be produced by the vibration of the diaphragm at the small end of the horn. However, if this diaphragm is allowed to vibrate freely in the air, without any kind of horn in front of it, it creates relatively little

sound. The reason is that the diaphragm does not adequately "couple" with the air, that is, the area of the diaphragm is so small that only a very small amount of air is set into vibration by it. The sound waves which proceed outward from this center of disturbance are relatively feeble ones. The advantage of the *cone* loud speaker over a simple vibrating diaphragm, (like the diaphragm of a telephone), is that the cone possesses a much larger vibrating surface. Accordingly, it sets much greater masses of air into vibration. This produces and discharges far more intense waves of sound.

The advantage of any form of *horn*, comes from a similar ability to set more air into vibration in correspondence with the vibration of the diaphragm. The diaphragm at the inner end of the cone of air contained inside the horn, sets this entire cone of air into vibrations like those of the diaphragm itself. In effect, the radiating surface from which sound waves are emitted becomes, not the relatively small surface of the diaphragm itself, but the entire front surface of the cone of air contained within the horn. The horn causes the air pressure per square inch over the surface of the diaphragm to be many times greater than if the diaphragm were to vibrate in free space. It therefore enables it to transfer its energy more efficiently to the atmosphere by means of the column of air inside the horn. The horn really makes the diaphragm work harder!

470. Possible shapes of horns: Horns can be made in many different shapes and sizes as shown at the right of Fig. 355, but it has been



Courtesy Amplion Products Corp.

Fig 355—Left A 12-foot air column horn for public address and sound picture work. It has two moving-coil driving units with a total power capacity of 50 watts. The bell opening is 45 inches square
Right Various horn shapes which conform to well-known mathematical equations.

proved experimentally that certain shapes are most suitable as they produce best results in practice.

Straight pipes of uniform diameter are unsuited for loud speaker horns because they are efficient resonators only within certain narrow frequency limits corresponding to the fundamental tone, and may increase the sound energy in these narrow frequency bands thousands of times. Outside of these narrow frequency-bands, no in-

crease in sound energy is brought about. Horns of various shapes have been designed and any one of these is better than a straight pipe for a loud speaker, because horns have less pronounced resonant properties than pipes.

The straight pipe (A), and horns of various possible shapes are shown in Fig. 355. The manner in which the cross-section area increases as we proceed from the *throat* to the *mouth* or *bell* of these horns, is determined by well known mathematical equations. The results obtained with horns of these shapes differ greatly. The shape which seems to give best performance for practical loud speaker work is that which follows the "exponential law", or a slight modification of it. Of all the horns having a given size (i.e., same length and terminal areas) the exponentially shaped horn is the most uniform sound radiator over the required range of audio frequencies. Since this is the best, the other shapes will not be considered here.

471. Exponential horns: A true *exponential*-shaped horn is one whose cross-section area doubles for equal increases in length, that is, the area of the horn varies as an exponent of the length. That is all there is to the exponential law. The law says nothing about how long the intervals of length should be—they may be any value we please. For instance we may have a horn whose throat area is say one square inch. The horn may be shaped so that its cross-section area doubles for every three inches of length, for every six inches of length or for every *five* feet of length, etc. Each of these would be a true exponential horn. If the area doubled for every foot of length, the area would be 2 square inches at 1 foot from the throat, 4 square inches at 2 feet, 8 square inches at 3 feet, 16 square inches at 4 feet, etc. The amount by which the horn increases in cross-section area for each unit of its length is called its *expansion ratio*. This may be varied, making long narrow horns of slow expansion, or short wide horns of rapid expansion, all of them still retaining the essential exponential principle; the principle by which the cross-section area of the horn increases by the factor two for each equal increase in length. This exponential rate of increase is sometimes called the *law of organic growth*, as it is the same rate at which most plants, trees and other organic bodies increase in size. The shell of a snail for instance, is an example of a true exponential horn.

As may be shown mathematically from its detailed theory, the advantage of the exponential horn, is that it permits the preliminary communication of the sound to the internal cone of air, and thence to the general air outside, to take place with the minimum of interference and resistance. In technical terminology, the exponential horn "loads" the diaphragm more completely and with less distortion for a wide band of frequencies, than can be accomplished with other existing shapes of horns. The increase in cross-section area is such, that as the sound wave disturbance travels from the diaphragm at the throat of the horn out to the bell, it expands uniformly over a wider and wider area without any

sudden changes or restrictions. Also, the bell of the horn is of such shape that the sound wave disturbance communicates to the outside air smoothly at the point where it leaves the horn. A typical commercial form of folded exponential horn used in public-address work is shown at the left of Fig. 355. Other forms are shown in Fig. 356.

472. Cut-off frequency: When correctly designed, an exponential horn radiates the sound waves uniformly over a wide range of frequencies. It reproduces these frequencies uniformly down to a certain definite frequency called the *lower cut-off* frequency, below which very little or no radiation takes place. The low frequency cut-off is determined by the rate of expansion of the horn. A horn which doubles in area for every foot of length will reproduce down to 64 cycles per second; one expanding half as rapidly (area doubles for every two feet of length) will respond down to 32 cycles; one expanding twice as rapidly (area doubles for every 6 inches of length) will respond down to 128 cycles per second, etc. The greater the rate of taper, the higher is the frequency of cut-off.

473. Considerations in horn design: The length of the horn is determined by several factors. First, a properly designed horn should be free from noticeable resonance. To prevent this, the mouth of the horn should be made large enough to transmit the sounds coming from it to the surrounding atmosphere without any great amount of restriction, since this would cause a back-pressure to be developed which would oppose the sound waves. It has been found that if the diameter of the mouth is made comparable to one-quarter of the wavelength corresponding to the cut-off frequency of the horn (as determined by its rate of expansion), the resonance in the horn will be negligible. The wavelength of sound in feet is determined by dividing the velocity of sound in feet per second (1130) by the frequency. So the horn should be extended until the mouth has a diameter about one-quarter the wavelength corresponding to the cut-off frequency. If the horn section is approximately square, the area of the mouth should be as large as that of the circle having this diameter. For instance, following out this reasoning a horn whose cut-off frequency is 64 cycles, (corresponding to a wavelength of 1130 divided by 64, or 17.7 feet), should have a mouth about 17.7 divided by 4, or 4.4 feet in diameter if circular; or about four feet by four feet if square.

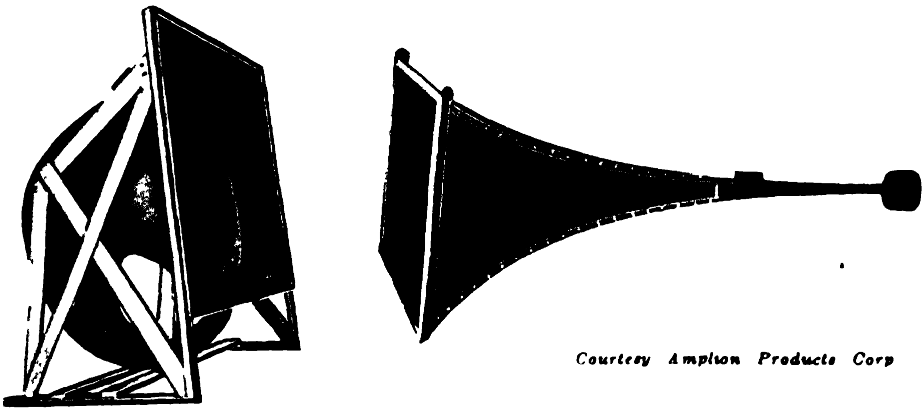
The diameter of the small end, or throat of the horn, depends on several factors. Since the diaphragm really act like a piston, sending waves of compression and rarefaction up and down the air column, if the area of the throat is small compared to the area of the diaphragm, practically all of the movement of the layers of air molecules near the surface of the diaphragm will cause a larger motion of the molecules through the throat. However, if the throat is made too small, compared to that of the diaphragm, a throttling effect will result due to the restriction of the air waves. If it is made too large, the diaphragm is not loaded properly. Also, in order to use a slow rate of expansion of the horn to obtain low cut-off frequency, the initial opening should be large or else the horn must be made too long to be practical, since it should be made long enough so that the diameter of the opening of the mouth or bell is at least equal

to ¼ the wavelength of the lower cut-off frequency. A compromise must therefore be made between these factors in the design of the horn. A special form of throat design which eliminates many of the troubles which usually occur at this point will be described in Article 476.

474. Design of an exponential horn: As an example of how exponential horns may be designed, let it be required to design one having a cut-off frequency of 32 cycles and to be used with a driving unit having a ⅝ inch diameter opening. The design procedure follows:

If the cut-off frequency is to be 32 cycles, the exponential horn must double in cross-section area every two feet. The cut-off wavelength will be 1130 divided by 32, or about 35 feet. The diameter of the mouth or bell should then be 35 divided by 4, or about 8.75 feet.

The area of the throat is equal to the square of the diameter times 0.7854, or 0.314 square inches. As the area doubles for every two feet, at a point two feet from the throat the area is $0.314 \times 2 = 0.628$ square inches, at six feet it is $1.256 \times 2 = 2.512$



Courtesy Racon Elect Co

Courtesy Amplion Products Corp

Fig. 356—Left. 14 foot coiled exponential horn used for reproduction of speech and music in theatres
Right A typical 6 foot exponential trumpet or horn used for reproduction of speech only, in public address systems It has a bell 28 inches square

square inches, etc. This is carried out until such length when size of the mouth or bell, determined by the cut-off frequency is reached. This figure for the bell size must be converted into area. Actually, the length of this horn would have to be about 28.5 feet. It is evident that such a "true exponential horn" would be large and unwieldly for home use. In practice, so-called exponential horns built for home use are not true exponential horns but are about seven or ten percent exponential. That is, each succeeding area is not double that of the previous section but is about seven per cent of this double value.

The results obtained with such horns are not as good as with those of the true exponential type, but the sacrifice in operating quality must be made on account of the small allowable size of the horns if they are to be used in homes. This is probably the most important reason why horn speakers are not used extensively in home radio receivers—simply because speakers of this type designed to have a low cut-off frequency, and give good reproduction of both speech and music, are necessarily too large and unwieldly. However, they are used extensively in connection

with sound pictures, and public-address and announcing systems, where their large size is not particularly a disadvantage, but their comparatively high efficiency and directional properties are important. An exponential horn of large size used in theatres and public-address systems is shown at the left of Fig. 356. Horns of this type are capable of splendid reproduction of speech and music. An exponential trumpet for the reproduction of speech only, typical of the type used in public address systems, is shown at the right. Since this is not called upon to reproduce frequencies as low as those which are encountered in music, its cut-off frequency may be higher, and its length is therefore much shorter.

475. Material and shape of the horn: The material of which the horn is made, is important. Although a horn may be well designed and constructed to correct size, total length, rate of expansion, etc., it may still fail to provide good reproduction, simply because of resonance effects in the material used for it.

The material used should have no marked resonant frequency, unless this resonant frequency is very low. One manufacturer uses a special construction of fleeced underwear cloth moulded together to correct shape and impregnated by a special binder compound. Another uses a special composition consisting of wood sawdust held by a binding compound and moulded to correct shape. Others are made of papier-maché. Large horns and trumpets are usually made of selected wood, properly treated. The inside surface of the horn should be smooth, to prevent the formation of eddies due to the moving air.

It is evident from the calculations in Art. 474, that the old types of short horns one or two feet in length, cannot possibly reproduce the low notes in music. The best they can do is reproduce the higher harmonics of these notes, and the ear responding to these makes it appear as though some of the low notes were being heard. Exponential horns which do reproduce the low notes must necessarily be long. In order to make these speakers more compact than they would be if straight, they are constructed in coiled or folded form, and even divided into parts. This does not harm the reproduction in any way, provided the bends are not too sharp and the cross-section areas follow the design equations chosen. A straight exponential horn is shown at (A) of Fig. 357. The cross-section area doubles for each equal increase of distance along the length, as represented by the dotted lines. This corresponds to the horn shown at the right of Fig. 356. At (B), the same horn is shown coiled or folded up to make it compact. This corresponds to the horn shown at the left of Fig. 356. The horn may also be folded as shown at the left of Fig. 355 A compact type of folded exponential horn developed by the engineers of the Bell Telephone Laboratories is shown at (C) of Fig. 357. The path of the sound waves is shown by the arrows, the driving unit and diaphragm being placed at the opening in the center of the rear side. The mouth of the speaker is toward the right in the illustration. Notice that the sound wave path divides into two identical folded paths which both

terminate at adjacent sides at the mouth of the speaker. Horns of this general type are employed in the "orthophonic" phonograph, in fact, exponential horns are sometimes called *orthophonic horns*. Large horns, of special folded construction to make them very flat, are used in moving picture theatres in connection with the sound accompaniment. They are mounted directly on the back of the special motion-picture screen and are raised and lowered with it, as shown at the left of Fig. 495.

476. Moving-coil horn units: The balanced type moving-iron form of driving unit provided with a suitable diaphragm, is used on many horns employed in public-address systems, simply because it eliminates running the two extra wires required for the field supply current. This, of course is an important advantage where a network of speakers is mounted over a wide area on poles or buildings, etc. However, where a large

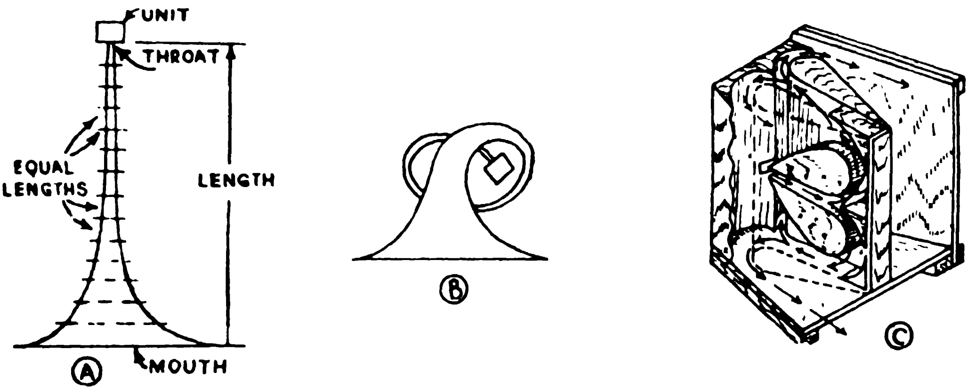


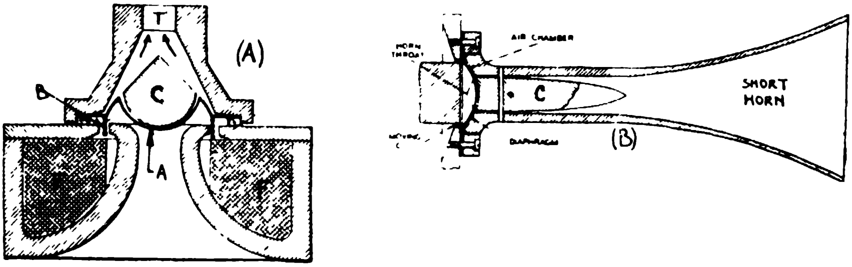
Fig 357—A given horn may be made straight, as at (A), coiled as at (B), or folded as at (C) Its characteristics will be the same in each case, provided the bends are gradual and not sharp

volume of sound is to be produced, the moving-coil type of speaker unit is usually employed, to prevent rattling. This is especially true in speakers used in theatres and halls, where a large volume of sound must be produced and the driving units must handle a considerable amount of power. A cross-section view of a very efficient form of moving-coil driving unit developed by the Bell Telephone Laboratories for this purpose, is shown at (A) of Fig. 358.

The field magnet F, is an electromagnet of efficient design providing a very strong field in the air gap in which the moving coil B, is suspended This coil consists of a single layer of aluminum ribbon .015 inch wide and .002 inch thick, *wound on edge*, the turns being insulated and held together by a thin film of insulating lacquer. The impedance of the coil is practically a pure resistance, and nearly constant at various frequencies. The coil is attached to a duraluminum diaphragm A, which is of unusual shape.

One of the things which may limit the sound radiating efficiency of the horn type of loud speaker is the interference between the air waves as they pass through the chamber between the diaphragm and the throat of the horn. In this speaker, the air chamber is so constructed, that no serious phase differences can occur within the useful range of frequencies. The stationary conical block C, is responsible for this.

Another factor, is the desirability of having the diaphragm vibrate to and fro as nearly like a rigid plunger as possible. An ordinary flat piece of metal clamped around a circular edge assumes a domed shape when vibrating at low frequencies. The diaphragm can be made to vibrate with its central portion essentially unflexed by adopting a shape which makes it less rigid near the edge, and more rigid toward the center, and then applying the force uniformly around the outside of the central portion.

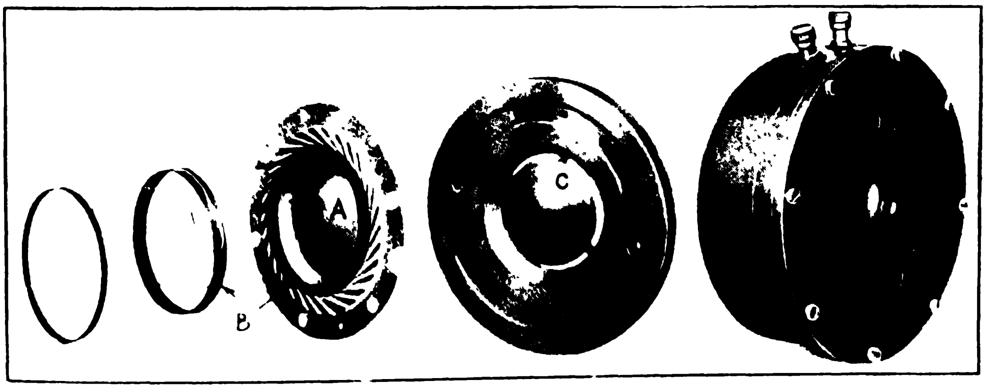


Courtesy Bell Telephone Laboratories

Fig 358—(A) Sectional view of the moving coil driving unit shown in Fig 359. (B) Sectional view of special short-horn speaker designed for high audio-frequency reproduction only This speaker is shown in Fig 360

These things are accomplished by the shape of diaphragm illustrated by A. It is made of a single piece of sheet aluminum alloy 0.002 inch thick. To this is rigidly fastened the driving coil B of circular form. In the assembled receiver, it moves up and down in the annular space between the ring-shaped pole pieces of the electromagnet. Between the coil and the clamped edge, the diaphragm is corrugated tangentially to prevent resonance.

The damping action of the thin air chamber between the conical block C, and the diaphragm, together with the loading effect of the horn, produces a constant load on the diaphragm, and a very flat frequency characteristic. The tapered opening under the diaphragm is to avoid resonance effects at its rear. The parts of the unit are



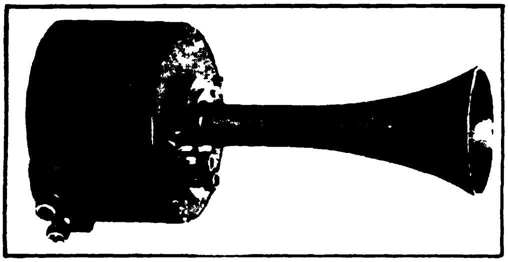
Courtesy Bell Telephone Laboratories

Fig 359—Details of the construction of the high-efficiency moving-coil horn speaker unit shown at (A) of Fig 358 The driving coil B, is attached to the diaphragm A which fits under the conical piece C The tangential corrugations on the disc are plainly visible

shown unassembled in Fig. 359, each part being labeled with a letter to correspond to that in Fig. 358. The cone shaped diaphragm A, and the tangential corrugations are plainly visible, as is also the conical block C. The complete unit is shown in its case, at the right.

An outstanding feature of this special form of driving unit is the high efficiency with which it converts the electrical power fed to it, into that of sound. In the commercial models, efficiencies as high as 30 per cent are realized—as compared with about 5 per cent for the usual cone type moving-coil speaker. When it is recalled that the resulting sound intensities are only a few decibels lower than those to be obtained at one hundred per cent efficiency, it will be understood that little is to be gained from any further increase in efficiency, except insofar as reduction in the percentage of loss enables greater power to be handled without exceeding a safe operating temperature. When coupled to a suitable horn, *fifteen watts* of sound power can be radiated. It reproduces frequencies from 60 to 6,000 cycles per second without distortion, and reproduces down to 40 cycles and up to 8,000 cycles with distortion so slight that it is almost impossible to detect it.

477. Special high-frequency loud speaker: The frequency range above 5,000 cycles contributes greatly to the naturalness of reproduction of certain sounds. Many instruments of the orchestra, such as



Courtesy Bell Telephone Laboratories

Fig 360—A special form of moving-coil loud speaker designed for the efficient reproduction of only the high audible frequencies from 6,500 to 12,000 cycles per second A section view is shown at (B) of Fig 358 Notice the short horn employed

High-frequency horns of this general type are commonly called "tweeters" because they produce the very high-frequency sounds

the violin, flute, snare drum, clarinet, cymbals, as well as voices (particularly female voices), have harmonics above 5,000 cycles which if suppressed, cause an appreciable change in the character of the sounds. This alteration in some cases is not especially objectionable, but in the reproduction of many common sounds of an impulsive character such as result from hand clapping, footsteps, tearing or rustling of paper, or the jingling of keys or coins, the suppression of the high frequencies may cause the reproduced sounds to bear but little resemblance to the original. Extension of the frequency range of the reproducing system to include the very high frequencies results in a marked improvement in the reproduction of these impulsive sounds and in the naturalness, color, and brilliance of reproduced speech and music.

Since ordinary forms of loud speakers are inefficient for reproduction of these audio-frequency sounds, due to the excessive mass and stiffness of the vibrating structure, etc., a special form of speaker is required for their reproduction A special form of speaker by which it has been possible to obtain efficient radiation of the high frequencies up to about 12,000 cycles is shown at (B) of Fig. 358. This speaker is intended as an addition to either a usual cone or horn type speaker to extend the range of efficient performance to about 12,000 cycles. Its *lower* cut-off point occurs at

about 6,500 cycles. This corresponds to the *high* cut-off point of most speakers. The removal of the necessity for low frequency reproduction with this speaker permits a more delicate mechanical structure having less mass, and makes it possible to extend the high frequency cut-off.

The diagram is a sectional view showing on an exaggerated scale the diaphragm, air chamber, and horn construction. The diaphragm is of .005 cm. duralumin, with a spherically embossed section at the center 2.5 cm. in diameter to provide rigidity; the edge outside this formed center is plane. A self-supporting moving coil of edgewise wound aluminum ribbon is attached directly to the diaphragm at the junction of the embossed and plane sections. A shoulder on the horn clamps the plane section of the diaphragm on a diameter, to increase the edge stiffness. The mass of the diaphragm plus the moving coil (within the clamped surface) is only about .16 gram. Since the frequencies to be reproduced are high, the horn has a mouth only two inches in diameter. The angle of the flare is 90 degrees. The efficiency of the unit is about 20 per cent.

Satisfactory results have been obtained by using this loud speaker in conjunction with both baffle and horn type loud speakers of the ordinary types which reproduce up to about 6,000 cycles. It may be mounted with the horn mouth extending through a baffle board adjacent to one or more baffle speakers or it may be suspended in the mouth of a large horn. The combination is most suitably coupled electrically by means of a network that causes the electrical power within a pre-determined frequency range to be delivered to the particular loud speaker that is efficient in that frequency range. This avoids a loss in efficiency and at the same time prevents rattling or damage to the high-frequency loud speaker which might be caused by large amounts of power being fed to it at low frequencies.

478. The condenser-type loud speaker: The *condenser* or *electrostatic type* of loud speaker has many worthwhile inherent advantages over the magnetic forms of speakers, although it has not been entirely successful commercially in the United States. It operates on the principle of the electrostatic attraction and repulsion of two electrically charged plates in accordance with the well known principle of electrostatics that *like charges repel* and *unlike charges attract*. The speaker itself really forms a large 2-plate condenser. It operates as follows:

When two conductors of electricity are separated in space by an insulator, and a difference of electrical potential is maintained between them they form an electrical capacitor or condenser. If they are both charged positively, they tend to repel each other, if they are both charged negatively they also tend to repel each other; if one is charged positive and the other is negative they attract each other (see Article 13). Suppose these two conductors are large, flat, metallic plates of equal area, separated by a thin film of air as shown at (A) of Fig. 361. If a difference of potential or voltage is applied to these plates, a force will be exerted tending to draw these plates together, and the force will be proportional to the area, A, of one side of one plate; it will be proportional to the square of the voltage between the two plates; and it will be inversely proportional to the square of the distance, D, between them.

From the above it is seen that the greater the voltage the greater the force, the larger the size of the plate the greater the force, and the smaller the distance between the plates the greater the force. If we make one of these plates quite heavy and stationary and the second plate very light and movable as shown in (B), the application of a varying voltage to them will tend to draw the light movable plate to the heavy stationary plate with a force which will increase *as the square of the voltage*. If an alternating voltage (for example the usual 60-cycle 110-volt house current) is applied between the two plates, the movable one will tend to move in and out at double the frequency of the applied voltage which, in this case, would amount to 120 times per second. This result would be obtained since the plates tend to pull together

both on the positive and on the negative *halves* of each alternating-voltage cycle. Thus instead of obtaining a 60-cycle tone by virtue of the motion imparted to the surrounding air by the movable plate, we would obtain a 120-cycle tone. This is a perfect instance of complete distortion, since the original tone is absent and is replaced by one of double the frequency, (one octave higher). Suppose that this alternating house current be replaced by the voice current from the output of a broadcast receiver. Then the light movable plate, which we shall henceforth call the diaphragm, would produce a hopelessly distorted sound since it would move in accordance with the *square of the voice voltage* and at *double the voice frequencies.*

479. The polarizing voltage: Let us now see how these difficulties are eliminated in a practical speaker of this type.

Suppose a high direct voltage, say 500 volts, is applied to the plates of our crude condenser speaker. There will be a strong steady attraction between them, due to the charges placed on them by this difference of potential. This is called the *polarizing*

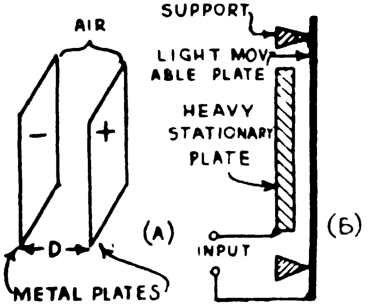
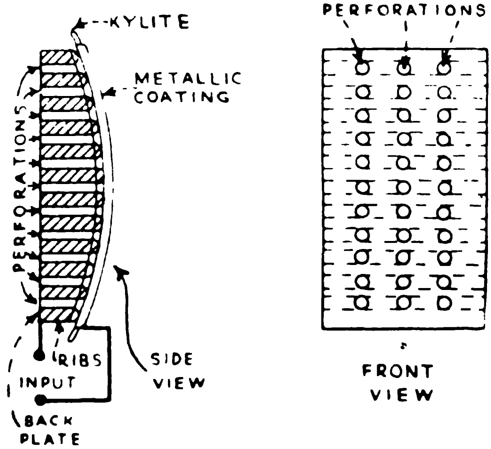


Fig 361—(A) Formation of simple condenser with 2 plates (B) Simple electrostatic loud speaker with one rigid plate and one light, movable plate



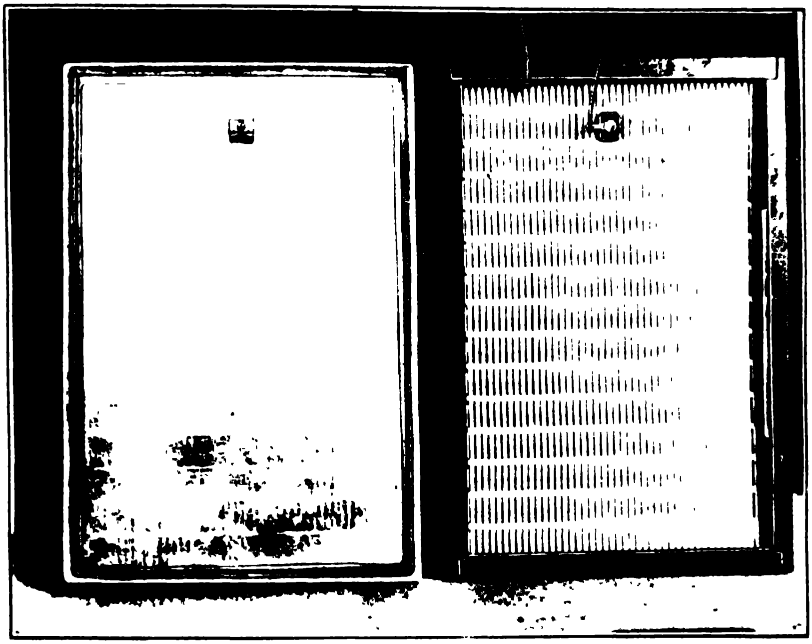
Right Side and front views showing the construction of the Kyle condenser speaker shown in Fig. 362

voltage. If now, we superimpose the much weaker a-c signal voltage upon these same plates at the same time, this alternating voltage will tend to increase and decrease slightly the steady direct potential difference which we have already established between the plates. In other words, the force will alternately become a little greater and a little less than the initial force due to the direct voltage, but, since the potential of one plate will always be of one polarity with respect to the other plate, this tendency toward double frequency response is greatly reduced.

It can be shown mathematically, that the motion of the diaphragm under these conditions will be approximately in accordance with, and proportional to the alternating voltage applied between the plates. The smaller the ratio of the alternating voltage to the constant applied direct voltage, the more accurately the diaphragm will follow the alternating voltage variations. It is exceedingly important to note that there will always be a component of the motion which is *twice* the frequency of the original voltage and also that the motion will never be *exactly* directly proportional to the applied alternating voltage In other words, in this type of loud speaker, as well as in the magnetic and electro-dynamic types, there is always some inherent distortion. A mathematical analysis of the condenser-type loud speaker shows that the greatest response is obtained when the plates are as close as possible together and both the constant direct voltage and the alternating applied voltage are as great as possible

480. Practical form of condenser-type speaker: The back or stationary plate of the commercial form of condenser-type speaker shown

at the right of Fig. 361 and in Fig. 362, is rigidly made of stiff metal, either iron or aluminum. Aluminum is preferable due to its non-corroding properties. The back plate is perforated with slots to prevent compression of the air between the plates. In order to obtain a large force on the moving plate, the dielectric must be as thin as possible, must have a high dielectric constant, and a high breakdown voltage, and must be very flexible. In the speaker shown in Fig. 362, the back plate is covered by a thin, stretched, rubber compound called "Kylite". This is about .005 inch-



Courtesy United Reproducers Corp.

Fig 362—The simplicity of the construction of a condenser speaker is shown here. The movable foil surface is shown at the left and the rear view showing the rigid aluminum stationary perforated plate is at the right No coils, magnets, cones, horns, etc are employed

es thick, has a dielectric constant of about 3, and has a breakdown voltage of at least 2,000 volts for this thickness. A thin, beaten tinfoil leaf about .0001 inches thick, is cemented on the outside surface of the Kylite sheet. Units about 8 x 12 inches in size are made up in this way. Any number of these units may be connected in parallel, in order to obtain a large surface from which to radiate the sound waves. The capacitance of each section is about .004 mf.

Just as with loud speakers of the free-edge cone type, it is necessary to use a baffle-board or baffle cabinet in order to radiate the lower audio-frequency tones. The same rules apply to the calculation of baffles for this purpose as in the case of cone-type loud speakers, (see Art. 467).

481. Connections of the condenser-type speaker: When a speaker of this type is used, the radio receiver with its associated audio-frequency amplifier must have the same properties as those required for good reproduction with magnetic and electro-dynamic loud speakers, with the exception of the arrangement of the circuit for the output of the last audio-frequency stage, and the provision of a suitable polarizing voltage.

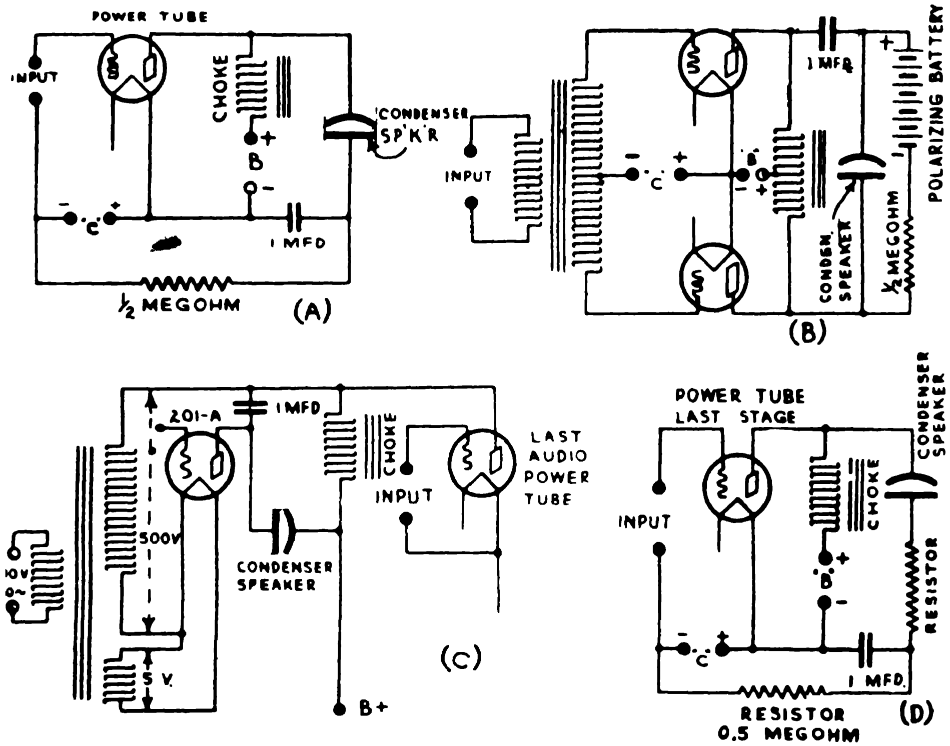


Fig 363—Several possible circuit arrangements for connecting a condenser type loud speaker to the power amplifier stage of the radio receiver

Whereas the impedance of the moving-coil type loud speaker is usually very low, averaging approximately 25 ohms at 1000 cycles, and the impedance of the average magnetic-type loud speaker is about 4,000 ohms at 1000 cycles, the impedance of the condenser-type loud speaker is very high; that is, of the order of magnitude of 50,000 ohms at 1000 cycles. It is, therefore, evident that circuit arrangements must be somewhat different in the case of the condenser loud speaker, in order to obtain the proper impedance relationship. If a transformer is used to couple the loud speaker with the output tube of the audio frequency amplifier, it must have a step-up impedance ratio instead of the step-down ratio which is usually employed for other types of loud speakers. The last tube may be impedance-coupled as shown at (A) of Fig. 363. However, if a low plate impedance power tube is used in the last stage, this is a very inefficient method of connection. A method for connecting this loud speaker with a push-pull amplifier is shown at (B). Where the last tube in the set is a power tube, such as the 210 or 250, the "B" voltage may also be used as the polarizing potential for the condenser loud speaker, as shown at (A). Sometimes it is desired to use a separate source of polarizing voltage in which case a step-up transformer, a 201-A type tube, and a 1 mfd. filter condenser are connected as shown at (C), to provide

the polarizing voltage. As the polarizing voltage is operative only when connected so as to give a closed d-c path for the biasing charge, a ½ megohm grid leak resistor has been shown in these diagrams where the output circuit contains a condenser. This completes the d-c path, and the 1 mfd. condenser allows the completion of the a-c path through the speaker.

Since the impedance of the condenser-type loud speaker is inversely proportional to the frequency, the division of voltage between the resistance of the last stage tube and the condenser-type loud speaker will change with the frequency; the voltage across the loud speaker being greatest at low frequencies and smallest at high frequencies. This quality can be compensated by proper design of the coupling transformer or by the introduction of resistance in series with the condenser-type loud speaker, as shown at (D). The resistor used must be of the best quality in order that no extraneous noise shall be introduced into the loud speaker circuit. The latter method improves the frequency-response characteristic at the expense of the sensitivity of the loud speaker, hence a compromise must be effected between the two. A value of about 15,000 ohms is recommended for a single section Kyle speaker, about 25,000 ohms for four sections, etc. It is, of course, possible to design the audio-frequency amplifier of the receiving set in such a manner as to have a rising frequency-response characteristic which will compensate the falling frequency-response characteristic of the condenser-type of speaker. In this way, maximum response may be obtained, with a fairly flat overall audio frequency-response characteristic.

482. Limitations and advantages of the condenser-type speaker: One of the first limitations of this type of speaker is that we must apply the direct polarizing voltage which must be very much larger than the alternating signal voltage applied, in order to minimize distortion. Second, the polarizing voltage must not be increased beyond 500 or 600 volts because of the danger of break-down between the fixed plate and the diaphragm. Further, it is not safe nor practical to generate much higher voltages than 600 for such a purpose. Third, the distances between the plates cannot be made indefinitely small for several reasons: (a) because the polarizing voltage would tend to puncture the insulation between the two plates if the distance were too small; (b) there must be sufficient distance so that the diaphragm may move back and forth in order to impart a mechanical wave-motion to the air in front of it; (c) if this distance were too small, the diaphragm might actually strike the stationary plate causing a short-circuit if too great a voice voltage were applied or if resonance existed either in the electrical circuit or in the mechanical construction of the loud speaker. Hence, it is seen that compromises must be effected throughout in the design of this type of loud speaker just as in the case of the magnetic and electro-dynamic loud speakers considered in previous articles.

As a result of these compromises, the sensitivity and efficiency of the condenser loud speaker is, in general, low. Due to the small permissable distance between the diaphragm and the back plate the large amplitudes of motion necessary for the adequate radiation of low tones is difficult to attain in a practical speaker of this kind. This makes it difficult to obtain adequate response at the low frequencies, although the audio amplifier used ahead of the speaker can be designed with over-accentuated low-frequency amplification to compensate for the decreased sensitivity. The problem of developing a suitable dielectric material which has all of the desirable properties mentioned above and yet which does not deteriorate rapidly, has probably been the greatest problem in the successful commercial development of this form of speaker.

One of the main advantages of the condenser-type speaker is its simplicity of construction and very low cost. It has but one movable

part and contains no coils or magnetic field construction. It can be made very compact. The diaphragm is attracted as a whole over the greater part of its surface, instead of being actuated at a point as in most moving-iron and moving-coil constructions. This reduces the effects of complicated modes of vibration of the diaphragm with resultant multiple resonances. Another advantage is the practicability of using exceedingly thin non-magnetic diaphragms of great flexibility and low inertia, thereby making possible the reproduction of the higher audio frequencies. Also a large flat surface is usually better adapted to the radiation of sound than is a cone or horn, since directional effects are reduced, and the sound seems to come from all directions rather than from any one place.

483. Comparison of various types of loud speakers: The question of which of the type of speaker described in this chapter is best, does not permit of any single definite answer—for all of them have special operating characteristics which make them particularly desirable for certain classes of work. Ignoring electrical characteristics and confining attention to acoustic ones, there are three essential characteristics of a loud speaker. One of them is the *sensitivity*, that is, the sound intensity which the loud speaker emits for a certain electrical input (or a certain amplitude of vibration) of the diaphragm. The second is the amount of *distortion* which is produced, which means the degree (if any) to which the apparatus changes the acoustic characteristics of the sound vibrations emitted by the diaphragm. The third is what is called the "*cut-off*". This means the points of low frequency and of high frequency below which, and above which, sounds are not produced efficiently.

There is no doubt that among the magnetic class of speakers, the moving coil type is most suitable for normal requirements in modern radio receivers, on account of its ability to handle large signal voltages without rattling. The question of whether a horn or a cone should be used with the coil driving unit, is also one whose answer depends on the particular applications of the speaker.

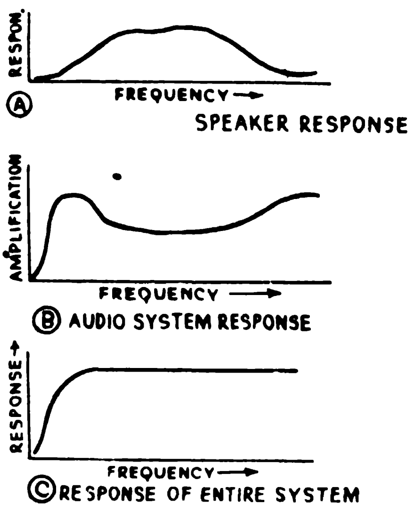
In freedom from distortion the exponential horns are quite satisfactory, but it is possible to avoid distortion with other types of loudspeaker also. The same is true of the matter of cut-off. The lowest frequency which a horn will emit, which determines its low-frequency cut-off, is not fixed by the exponential principle, but merely by the length and width of the horn and by similar characteristics. Either an exponential horn or a cone loudspeaker or some non-exponential variety of horn can be designed to have a low and favorable cut-off, emitting frequencies down to fifty or sixty cycles or even lower.

It is the first factor, that of sensitivity, which brings the exponential horn its greatest victories. With a relatively small amount of energy emitted from the diaphragm itself, the cone of air, expanding as the horn enlarges in accordance with the exponential principle, transmits an exceptionally large fraction of this diaphragm energy to the outer air. If the exact dimensions of the horn provide the desirable low cut-off and if the details of design are adjusted to minimize distortion, it is possible to obtain great volume, which means loudness, without interfering with the absence of distortion which is so necessary for first-class musical reproduction

It is for this reason that the horn type of speaker with an efficient form of moving coil driving unit, has been so very popular in all those applications where loudness is an essential factor; for example, where large audiences are being entertained as in theatres, halls, etc., or where music is to be provided for marching or for dancing.

For use in home radio receivers where the space available for the loud speaker is very limited, the cone type seems to fill the requirements best, because horns capable of reproducing down to the low audio frequencies are necessarily very long and large, even if they are of the folded type, whereas a cone speaker is small and compact. If the condenser type of speaker can be developed to a satisfactory commercial form with a suitable dielectric of long life, it is possible that it may yet supplant the cone type speaker for home use, on account of its relative cheapness and excellent reproduction when used with an audio amplifier designed especially to compensate for its deficient reproduction of the low-frequency sounds.

484. Desirable loud speaker characteristics: While it is desirable from the point of view of "naturalness of reproduction" in speech and music to reproduce faithfully all sounds up to 8,000 or 10,000 cycles per second, the use of any loud speaker, or speaker combination, that efficiently reproduces these extreme high frequencies imposes severe requirements upon the system with which it is operated. In systems using recorded programs, the "surface" or "ground noises" on both film and disc records becomes much more troublesome because much of this noise



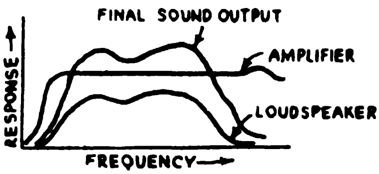


Fig 364—The frequency-response of the audio amplifier (B), and that of the speaker (A), must both be considered, since the results obtained (C), is really the combustion of both. The r-f amplifier should also be considered, since the high audio frequencies will be lost, if sideband suppression takes place in the r-f amplifier. Deficiencies in the frequency response of the speaker may often be compensated for in the r-f or a-f amplifier

energy is in the high frequency range. To realize the full value of improved high-frequency performance in the loud speaker, recordings with very low noise levels must be used, as otherwise the increased noise may be more objectionable than the loss of the high frequencies. Even in programs supplied by broadcasting circuits where there is no recording process, special care must be taken to exclude extraneous noises due to stray electrical disturbances such as are caused by atmospheric "static", electrical machinery and "power" leaks, etc. These might be quite tolerable if the system did not respond efficiently to the high frequencies. Amplifier overloading and any other distortion in the system is also much more readily detected by the ear when the high frequencies are present.

This tends to make it necessary to use higher powered amplifiers and better equipment throughout.

At the present time, these and other considerations seem to preclude the general use of a loud speaker capable of efficiently reproducing the entire audible frequency range. While the reproduction of the extremely high frequencies is an accomplishment greatly to be desired, it is nevertheless a refinement which cannot be achieved through improvement of the loud speaker alone; development of better apparatus and technique in the rest of the transmission and reproducing system must keep pace.

485. Combining audio amplifier and speaker characteristics: If definite knowledge regarding the frequency-response characteristics of a certain loud speaker is at hand, the audio frequency amplifier for use with it can be designed to supplement the loud speaker at its weak points, that is, at the frequencies for which the loud speaker is deficient, the amplifier can be designed to increase the response and conversely where the loud speaker response is more than normal, the amplifier can be arranged to reduce the response. As an example of this, (A) of Fig. 364 shows the response curve of a certain speaker. The low note reproduction is weak, the middle frequencies are normal and the high frequencies are weak. Obviously the audio amplifier should be designed to have the frequency response characteristics shown at (B), with the low and high frequency amplification exaggerated, and relatively lower amplification over the middle register. The approximate resultant response curve of the speaker and horn combined is shown at (C). Notice that the deficiencies of the speaker have been nearly corrected by proper design of the a-f amplifier. Obviously this amplifier would only give these good results when used with this particular type speaker, if another speaker were used the resulting response would be totally different.

Transformer-coupled or shunt-feed coupling by the Clough system lends itself nicely to this sort of work, since the amplification characteristic of the transformer can be modified easily. Also, certain frequencies can be suppressed by band filters, or strengthened by resonant circuits. This practice of compensating for the deficiencies of one electrical circuit by over-exaggerating the corresponding characteristics in another circuit in a system, is used extensively in telephone work. It is also possible in many cases to make up for certain deficiencies in the receiver characteristics by means of a loud speaker having special design features. Thus the high-frequency audio suppression caused by an r-f amplifier which is so selective that it cuts sidebands can be compensated for by the use of a loud speaker which properly over-accentuates the high-frequency notes.

It is evident from a study of the curves of Fig. 364, that all types of loud speakers will not operate equally well with all audio amplifiers. This is the reason why a certain loud speaker will appear to work very well with a particular set and may give only average results when connected to a different receiver. As a matter of fact, an audio amplifier having ideal straight-line frequency-response intensifies the poor frequency response

of a loud speaker of average worth, as shown, and really makes it sound worse than shown in the diagram at the upper right of Fig. 364.

It must be kept in mind however, that the difference in hearing facilities of different persons makes it impossible to produce one sound-reproducing system which is absolutely satisfactory to every person. Compromises must be made. Some persons are pleased with reproduction where all of the low notes are reproduced. Others are pleased with reproduction which includes only part of the low-note range, etc. Tone controls in the audio amplifier help to provide an adjustment of the frequency response to suit the individual tastes of the listener. It must be remembered that the compensating possibilities of the audio amplifier apply to frequency-response and not to any correction for wave-form distortion which may occur in either the amplifier or the speaker. This form of distortion is not so readily corrected.

Loud speakers should never be compared by listening to their reproduction when connected to a poor receiving set, since the better of the speakers will sound worse. This is due to the fact that the better the frequency-response curve of the speaker the more the defects of the receiver (especially overloading), will appear in the reproduction. If, however, two loud speakers are connected to a double-pole double-throw switch, the blade posts of which are connected to the ouput of a *good* set, which set is tuned to a *good local* broadcasting station, a useful comparison may be made. The relative intelligibility of speech is an indication of the presence of the higher audio frequencies. If "f," "s," "v," "b," "p," and "th" are *clearly* distinguishable, the loud speaker has a good high-frequency characteristic. If, when listening to the piano, the tones are deep and rich, the low-frequency characteristic is good; on the other hand, if the piano sounds thin and tinny the low frequency characteristic of the speaker is deficient. If the voice is full and clear and intelligible, and yet has an unnatural metallic quality, there is at least one high peak in the middle or upper range of the frequency-response curve.

486. Connecting several speakers together: The methods of connecting several speakers to the output circuit of the power amplifier stage of the audio amplifier will be considered in Chapter 30.

REVIEW QUESTIONS

1 What is the function of the loud speaker in the radio receiving system?
2. What is a loud speaker driving unit? Name three types of driving units?
3. What is the difference between a "moving iron" and a "moving coil" type driving unit?
4 Explain the operation of the iron diaphragm type of unit. What are its disadvantages?
5. Explain the operation of the balanced armature type of unit. What are its advantages and disadvantages?
6. Explain the operation of the moving coil type of unit. What are its advantages?
7. Describe the construction and operation of an electro-dynamic speaker designed to have its field operated from 110 volts a-c Why is the rectifier used?

8. What is the function of the coupling transformer between the plate circuit of the power tube and the voice-coil of an electro-dynamic speaker?
9. A speaker input transformer is to be designed to couple a 10 ohm voice-coil to the plate circuit of two '50 type tubes in push-pull. What must be the impedance of the entire primary of the transformer and the turns-ratio for most efficient transfer of the maximum undistorted output?
10. What is the purpose of the hum-bucking coil in a moving-coil speaker employing a dry-plate rectifier?
11. What are the advantages of obtaining the field supply current for an electro-dynamic speaker by connecting it as a choke in the B power supply unit?
12. How could you tell whether the voice-coil in a speaker needed re-centering or not? How would you proceed to re-center it?
13. What is a cone speaker? Define free-edge cone, fixed-edge cone. What is the function of the cone?
14. What is the function of the baffleboard used with a cone speaker? What baffle length is required for full reproduction of the 40 cycle note of a bass viol by a free-edge cone?
15. A cone-type speaker is installed under the radio receiver in a console cabinet. What must be the distance from the edge of the front face of the cone around the outside of the cabinet and inside to the back face of the cone, in order that sounds of frequencies as low as 100 cycles may be fully reproduced?
16. The cabinet of a midget type receiver measures 12 inches across, 18 inches high and 9 inches deep. The speaker having a 6 inch diameter cone is mounted directly in the center of the front of the cabinet. To what lowest frequency will the cabinet act as an effective baffle? If the diaphragm and driving unit are capable of vibrating as low as 100 cycles, will the notes down to 100 cycles be heard at all when this cabinet is used as a baffle?
17. A certain electro-dynamic speaker operating with a dry-plate rectifier delivering 2 amperes, and having a 1,000 ampere-turn field coil, is to be changed and connected so as to obtain its field current supply by connecting it as a choke coil in the filter system of a "B" power supply unit. When connected this way, 100 milliamperes will flow through the field. If the field is to be re-wound for the new condition, how many turns of wire must it have, and will it be re-wound with smaller or larger wire than before? Are any other changes in the speaker necessary?
18. Explain the operation of the inductor type speaker unit. What are its advantages?
19. What is the function of the horn on a loud speaker? What characteristics should the horn material possess?

20. What is an exponential horn? What determines its cut-off frequency? What are its advantages over other types of horns?
21. What is the advantage of the electromagnet type of moving-coil speaker over the permanent magnet type? For what applications does the latter type have special advantages?
22. Why is the horn used on the horn type loud speaker? How should the cross-section area vary along the length of the horn for best reproduction?
23. An exponential horn is to be designed with a throat ½ inch in diameter, and is to have a cut-off frequency of 64 cycles. What must be the length of the horn and what is the size of the bell, if it is square?
24. Why is the horn type speaker not used extensively in radio receivers designed for home use? Why is it used extensively in public-address and sound picture work?
25. What is the advantage of using two loud speakers, one designed to reproduce the low and medium frequencies and the other designed to reproduce the high frequencies?
26. What is the principle of operation of the condenser type loud speaker? Why is a polarizing voltage used?
27. What are the limitations of the condenser speaker? What are its advantages?
28. Draw a diagram of a condenser type speaker connected to a power output tube of a receiver, showing the necessary polarizing-voltage tube.
29. What characteristics are desirable in a practical speaker used with an ordinary radio receiver?
30. Draw the frequency-response characteristic of a loud speaker which does not reproduce either the middle or the high frequencies efficiently. Now draw the frequency-response characteristic of an audio amplifier system to work with it, such that it will tend to compensate for the deficiency of the speaker.
31. Why is it not advisable to employ loud speakers which will reproduce the audio frequencies up to 8,000 or 10,000 cycles, with present radio systems? What is lost by employing systems which only reproduce sounds of frequencies only up to 4,000 or 5,000 cycles?

CHAPTER 26

THE BATTERY OPERATED RECEIVER

TYPES OF BROADCAST RECEIVERS — APPLICATIONS OF BATTERY-OPERATED RECEIVERS — RECEIVER CIRCUITS — THE FILAMENT CIRCUIT AND SUPPLY — T-R-F RECEIVER — DETAILED ACTION OF THE RECEIVER — RECEIVER WITH SELF GRID BIAS — VOLTAGE AMPLIFICATION PRODUCED BY THE RECEIVER — LOUD SPEAKERS FOR BATTERY-OPERATED RECEIVERS — SUPERHETERODYNE BATTERY-OPERATED RECEIVER — REVIEW QUESTIONS.

487. Types of broadcast receivers: Now that we have studied the characteristics, construction and circuits of the various components which go to make up a radio receiving system, we may proceed with the study of complete receivers themselves. We will consider those receivers designed for reception of signals in the ordinary broadcast band of frequencies from approximately 500 kc to 1500 kc, first. Short wave receivers will be studied in a later chapter, as they present special design and construction problems.

Radio receivers for broadcast reception may be classified according to the source of power which is used to operate their vacuum tubes. In one class we have the *battery-operated receivers* which employ either primary or storage batteries for this purpose; in the other are the *electric* receivers which obtain this power from the d-c or a-c electric light mains. The battery-operated type will be studied now.

488. Applications of battery-operated receivers: While it is true that electric operation of radio receivers possesses many important advantages over battery operation, there are many fields of application in which electrically operated receivers cannot be employed, simply because no suitable or economical source of electric current is available. For instance, millions of farm and country homes are not supplied with electric current for lighting purposes, and therefore must resort to battery operated receivers. Even in many city homes, the same condition exists. Battery operation is also necessary for receivers operated in automobiles and aircraft. (The special forms of receivers for the latter purposes will be considered in Chapter 29). There is, therefore, a very definite field for battery-operated receivers which shall produce results as nearly as possible equal to those obtained from electrically-operated receivers.

489. Receiver circuits: There are two main types of circuits employed in battery-operated receivers; namely, the tuned radio-frequency circuit and the superheterodyne circuit. The perfection of screen-

grid, general purpose, and pentode tubes for economical operation from batteries has done much toward furthering the development of these circuits to a point where splendid performance is obtained. Since the detector tubes available for battery operation are not able to handle signal voltages as large as those which are commonly employed in electric receivers, the amplification obtained in the r-f amplifier must be kept down to a value such that the signal will not overload the detector tube. This means, in most cases that two stages of audio amplification are used following the detector in order to bring the signal strength up to good loud speaker volume.

490. The filament circuit, and supply: Most tubes used in battery-operated receivers (excepting those used in aircraft and automobile receivers), are of the direct-heater type, in which the filament current flows through the coated filament which is also the cathode, (as shown at (B) of Fig. 189). The construction of a three-electrode tube of this type is shown in Fig. 193, and that of a screen-grid tube is shown in Fig. 226. The filaments are connected in parallel across the source of filament voltage, usually with a variable rheostat included in the circuit to enable the operator to compensate for the drop in voltage of the battery as it nears the discharged condition, and thus maintain a more uniform voltage at the filaments. Circuits of this kind are described in Article 53. The parallel filament circuit of a typical battery-operated receiver is shown in Fig. 32. In Fig. 33 combination of five tubes is shown connected so that two rheostats are used to control the filaments. The source of filament voltage may be either dry cells, a storage battery or an Air-cell battery (see Article 65). Filament operation with dry cells is really so expensive and bothersome that it has nothing to recommend it unless the receiver is to be made very light for portable use. Likewise, the use of a storage battery is bothersome due to the necessity for frequent charging and the likelihood of sulphuric acid getting on to furniture, rugs, etc. However, there are many receivers still in use, which employ a storage "A" battery for filament supply. The development of the improved types of tubes having filaments designed for 2-volt operation, together with the perfection and use of the 2-volt Air-cell battery described in Article 65, has led to the development of very efficient battery operated receivers. Dry cell B batteries (see Article 62) of either the cylindrical cell or Layer-bilt construction are employed for "B" voltage supply.

The ordinary form of dry cell, described in Article 60, is not perfectly satisfactory as a source of filament voltage and current in radio receivers which are to be operated by batteries. Due to the fact that the internal resistance of dry cell increases greatly as it becomes older, the available voltage at its terminals (*p.d.*) when it is delivering current, drops lower and lower with use. Therefore, in order to maintain a constant voltage at the filaments of the tubes in a receiver using dry cells for filament voltage supply, a combination of dry cells initially supplying higher voltage than the filaments are designed for, must be used, (two or more 1.5 volt dry cells must be connected in series to obtain this voltage). A variable resistance (called the filament rheostat. Fig. 30) must be connected in series in the circuit to absorb the excess battery voltage when the cells are new. As the receiver is used and the terminal voltage of the cells drops, the resistance of the filament rheostat must be gradually

reduced, so as to maintain a constant voltage across the tube filaments. This arrangement is rather bothersome, and in actual practice the tubes are usually being burned above or below their rated voltage due to improper or careless adjustment of the rheostat. This results in very much shortened tube life.

The Air-cell "A" battery was developed to overcome this trouble, by providing practically constant voltage at its terminals throughout its entire useful life—that is, its internal resistance does not increase greatly with use. This makes it more suitable than the ordinary dry cell for the purpose of supplying a steady voltage to the tube filaments of battery operated receivers. Part (B) of Fig. 40 shows an interesting comparison of the voltage actually delivered at the filaments of a battery-operated radio receiver using seven tubes of the 2 volt type, drawing a total filament current of about 0.55 ampere. The set was used three hours daily. When a bank of 8 dry cells (2 groups of 4 cells each, the cells in each group being connected in parallel and the two groups connected in series to give 3 volts) was used to supply voltage to the filaments, it required 4½ dry battery renewals and installations (total of 36 dry cells) to operate the set for 1,100 hours. In each case the bank of dry cells was discarded when its total voltage dropped to 2 volts (the rating of the tube filaments). Notice from Fig. 40, how the dry cell voltage drops as the cells are used. Each bank of dry cells was only good for about 250 hours of operation. When the same receiver was operated from an Air-cell "A" battery, the voltage applied to the filaments remained practically constant (as shown in Fig. 40), throughout the entire life of the battery, (about 1,100 hours). As the cost of 36 dry cells is about double the cost of the Air-cell battery, and the latter provides the correct filament voltage throughout its entire life (600 ampere-hours capacity) its advantages are apparent.

Receivers designed especially to take full advantage of the characteristics of the 2-volt type of vacuum tubes will now be considered. These tubes are the '30 type general purpose tube, the '32 type screen-grid tube, the '31 type 3-electrode power tube, and the '33 type power pentode (see Fig. 214).

491. T-R-F receiver: A typical battery-operated receiver of the t-r-f type, designed for home use, is shown in Fig. 365. The r-f amplifier contains three tuned stages employing screen-grid tubes. The detector is of the grid-bias type and also uses a screen-grid tube. This is followed by one stage of resistance-capacity coupled a-f amplification feeding into a pentode power amplifier tube. By using resistance coupling, it is possible to place quite a high impedance plate load in the detector tube circuit in order to obtain efficient voltage transfer, since the a-c plate resistance of a screen-grid tube operated as a grid-bias detector is very high. The last audio tube is of the pentode type, for high power sensitivity. If an ordinary moving-iron type speaker is used, the use of a 30-henry choke and 2 mf. condenser for coupling it to the pentode tube as shown, is satisfactory. If a moving-coil type speaker is used, it must have an input transformer designed especially for operating between power pentode tubes of this type and the low-impedance voice-coil.

The four tuning condensers C_2, may be a single 4-gang condenser for single-dial tuning control. Choke coils L and by-pass condenser C are for eliminating interstage coupling in the common resistance of the "B" batteries. Volume control is obtained by means of the potentiometer R, which enables the screen grid voltage on the r-f tubes to be varied, and the amplification controlled. Rheostat R_1 provides a control for the filament voltage. The connections of the various batteries are shown. Three 45 volt "B" battery blocks are connected in series to obtain the 135 volts

necessary for the proper operation of the plate circuits of the tubes. Dry cell "C" batteries supply the proper grid-bias voltages.

492. Detailed action of the receiver: The various changes which an incoming signal voltage causes in the grid and plate circuits of the various tubes is shown above the circuit diagram. This should be studied carefully as it gives a graphic picture of what actually occurs in a radio receiver. The modulated r-f signal voltage induced in the antenna cir-

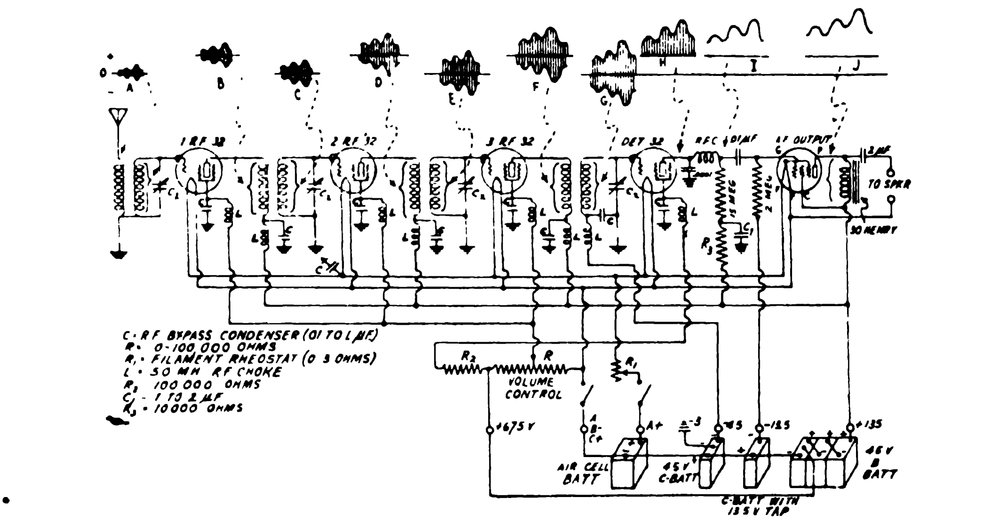


Fig 365—Typical screen grid t-r-f receiver using 2-volt type tubes and operated by an Air-cell "A" battery and dry cell "B" and "C" batteries A pentode power amplifier tube is used in the last audio stage. The changes which the modulated r-f signal voltage causes in the grid and plate circuits of the successive tubes when it acts on the input of the receiver, are shown by the graphs above Standard screen grid type tuning coils and .00035 mf tuning condensers may be employed. The graphs for the grid circuits represent the varying signal voltages applied to the grid. Those for the plate circuits represent the varying plate currents, caused by the signal voltage variations

cuit is transferred to the grid of the first r-f tube by the antenna coupling transformer. This alternating signal voltage is represented at A, and is applied to the grid circuit of the first r-f tube. This causes the plate current to vary in exact accordance with the r-f variations in it. The r-f varying unidirectional plate current flowing through the primary of the r-f transformer in its plate circuit, causes amplified voltages to appear across it as shown at B. The varying voltage is transferred to the secondary winding by transformer action, and acts on the grid circuit of the second r-f tube. T..is is repeated in each r-f stage, amplification taking place in each stage, and the voltages appearing as at C, D, E, F and G. Of course this desired signal is selected from all others by the tuned circuits of the r-f amplifier. In the plate circuit of the detector a very important action occurs. First of all, since the tube is operated at the lower bend of its characteristic, practically no plate current changes are

produced when each negative half cycle of the signal voltage is applied to the grid circuit (see (D) of Fig. 236). Hence, the lower halves of the signal variations are eliminated. The result of this action is shown at H. Due to the action of the by-pass condenser in the plate circuit, the r-f variations are removed from the plate current flowing through the 150,000 ohm coupling resistor, and the result is a current varying at audio frequency as at I, whose modulations are the same as those of the modulated r-f signal voltage at A. This audio-frequency voltage is amplified by the audio amplifier tube. The amplified output, appearing as at J, is fed to

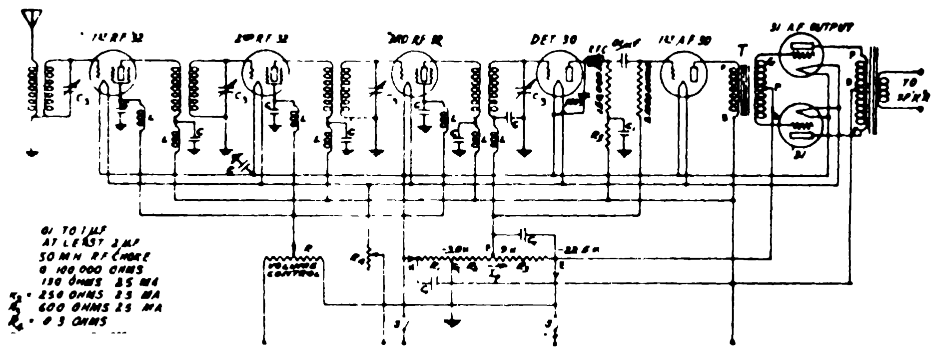


Fig 366—Typical screen grid t-r-f battery operated receiver with 2-volt type tubes A tapped resistor is employed for furnishing self-grid bias voltage to the various tubes—thus eliminating the usual "C" batteries A push-pull output stage is employed. Standard screen grid type tuning coils and tuning condensers may be employed

the loud speaker through the speaker coupling circuit, where it is converted into sound waves of the same wave-form and frequency. This completes the operation of the receiver. The additional energy added to that of the original incoming signal comes from the "B" batteries.

493. Receiver with self grid-bias: The circuit diagram for a simple battery-operated receiver in which the grid bias voltages are all obtained automatically by utilizing the voltage drops through resistors R_1, R_2 and R_3 of proper value for this particular tube arrangement, is shown in Fig. 366. This circuit differs from that in Fig. 365, in that a 3-electrode tube detector is employed, and a 3-electrode power amplifier tube is used, making the use of two audio stages necessary, the output stage being of the push-pull type. The first a-f stage is resistance-coupled to the detector and the second is transformer-coupled to the first a-f tube.

The combined plate current I_p of all the tubes, flows through resistances R_1, R_2 and R_3 in the direction of the arrows. This makes the potentials of points E, F and G lower than that of H. Since H is connected to the negative filament terminals of the tubes (from which point all grid and plate voltages of a tube are referred), and points E, F and G represent

the grid-return points of the power amplifier, detector and first audio, and r-f tubes respectively, it follows that the grids of these tubes are maintained at a definite negative grid bias potential with respect to their filaments. Resistors R_1, R_2 and R_3 are properly proportioned to apply the proper bias voltages to the tubes. Several advantages result from this form of circuit. First, no C batteries are required. Second, correct C bias is furnished to the tubes regardless of the condition of the "B" batteries. As the "B" batteries get older and their voltage drops, proportionately less plate current flows through these resistors and so the grid-bias voltages are correspondingly reduced to the proper value for the particular plate voltages which are being applied to the tubes. Since the grid bias voltage obtained by the voltage drop in the bias resistor, is being subtracted from the applied "B" battery voltage in this circuit arrangement, the effective voltage acting on the plates of the tubes is actually less than the applied "B" battery voltage by this amount. Therefore a higher "B" battery voltage than is ordinarily used must be employed, (157.5 volts instead of 135 volts), to make up for this. This is not necessarily objectionable since the battery connections are greatly simplified (compare with circuit of Fig. 365), and the problem of battery renewal and connection is simpler.

Since 3-electrode type power tubes are used in the last audio stage, they are connected in push-pull in order to provide ample handling capacity for even loud signals. A reduction of second harmonic distortion also results from this connection.

493A. Voltage amplification produced by the receiver: In order to obtain some idea of how much amplification of the weak signal voltage in the antenna circuit is produced by a radio receiver, we may calculate the overall voltage amplification of the receiver as shown in Fig. 366.

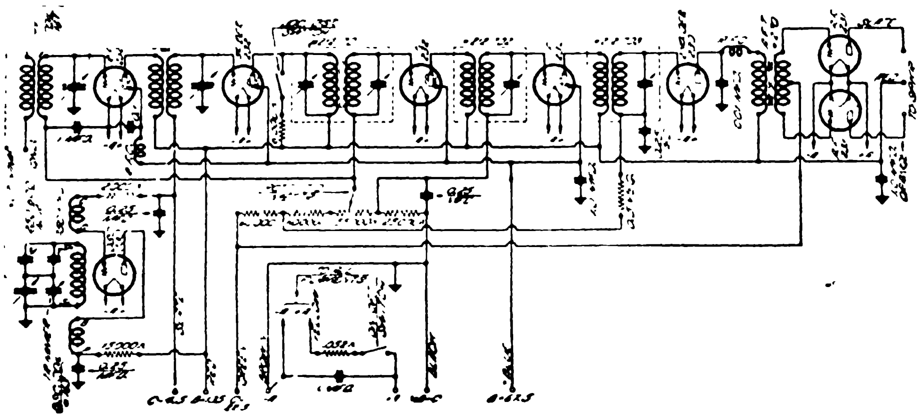
The input voltage applied to the first r-f tube is amplified by it, and appears as a larger voltage across its plate circuit load. This is stepped up slightly by the r-f transformer and appears in the secondary winding, where it is applied to the grid circuit of the following tube. This amplifies it in the same way, and so on through to the output terminals of the receiver. Let us suppose a gain of 5 is obtained between the antenna and the input to the first r-f tube. Now although the voltage amplification factor of the '32 type tubes employed as r-f amplifiers in this receiver is found from Fig. 214 to be 440, it is not possible to obtain this much amplification from the tube, because the a-c plate resistance is so high, (800,000 ohms), that the impedance of the r-f transformer primary connected in the plate circuit is small compared to this. Therefore only a small part of the amplification factor of the tube is actually made effective in practice. Let us suppose the actual voltage amplification produced by the detector is 3. We will suppose that the primary winding of the transformer. T connected in the plate circuit of the first a-f tube is of high enough impedance so that 90 per cent of the amplification factor (8.8) of the tube is realized. The ratio of this transformer. is 3 to 1. Also suppose that 50 per cent of the amplification factor of 3.5 is realized from each power amplifier tube. Then the amplification produced by the entire receiver is considered as follows:

Between antenna and grid of 1st r-f tube, 5; by first r-f tube and transformer, 30; by second r-f tube and transformer, 30; by third r-f tube and transformer, 30; by detector, 3; by resistance coupling, 0; by

first a-f tube, $8.8 \times .90$; by input transformer T, 3; by each push-pull tube, 3.5×0.50. Since the output voltages in the two halves of the primary of the push-pull output transformer combine additively, the total signal voltage appearing across the entire primary is 2 times this value. Therefore, the total amplification is:

$$5 \times 30 \times 30 \times 30 \times 3 \times 8.8 \times .90 \times 3 \times 3.5 \times .50 \times 2 = 34,000,000. \text{ approx.}$$

This amplification of approximately 34 million gives some idea of the large total voltage amplification which may be obtained by connecting several amplifier tubes in suitable cascade circuits, so that each tube amplifies the voltage output of the previous one. Suppose that the antenna of this receiver is situated in the field of a transmitting station such that 2



Courtesy Citizens Radio Call Book

Fig 367—Typical battery-operated superheterodyne receiver employing 1 t-r-f amplifier stage ahead of the first detector, and 2 intermediate-frequency amplifier stages A single push-pull output audio stage is employed

mierovolts (.000002 volts), is induced in it. Then the voltage appearing across the secondary of the push-pull output transformer would be:

$$.000002 \times 34,000,000 = 68 \text{ volts.}$$

The total voltage amplification produced by any receiver may be calculated in this way.

494. Loud speakers for battery-operated receivers: The possible choice of a suitable form of loud speaker for a battery-operated receiver is narrowed down to the use of either a moving-iron type cone speaker, an inductor type speaker, or one of the permanent magnet moving-coil type. These are described in Chapter 25. All of them are capable of very satisfactory results if they are well designed and constructed. The use of a moving-coil speaker employing an electromagnet type of field is not practical due to the fact that it is not economical to supply the electrical power required by the field, by means of batteries.

495. Superheterodyne battery receiver: A typical circuit diagram of a superheterodyne receiver designed for battery operation is

shown in Fig. 367. The special "pad" tuning circuit for the oscillator is necessary to equalize the tuning with that of the r-f and detector circuits in order that single-control tuning may be employed. Two stages of intermediate-frequency amplification are employed, the first stage coil being a sharply tuned band-pass filter. The second detector feeds directly to the push-pull output stage as shown. The filaments are all connected in parallel across the "A" battery supply terminals.

REVIEW QUESTIONS

1. Since electric operation of radio receivers presents so many advantages over battery operation, why are battery operated receivers used at all?
2. Draw the complete circuit diagram of a 5 tube t-r-f battery receiver employing two '32 type tubes for r-f amplification, a '30 type tube as a detector and one as the first a-f amplifier, and a single '31 type tube in the output stage. Both audio stages are to be transformer-coupled. Show the connections for all batteries also.
3. Show by means of a suitable diagram, and explain in detail, just what actions an applied signal voltage causes in the grid and plate circuit of each tube in a 5 tube t-r-f receiver.
4. What would happen if no detector tube were used in the above circuit? Explain in detail.
5. Name the various types of loud speakers with which you are familiar and give your reasons why each one may or may not be desirable for use with a battery-operated receiver for home use.
6. How do run-down "A" or "B" batteries affect the operation of the receiver?
7. How would you determine whether the "B" batteries needed replacement? How would you test the condition of the "A" battery, (a) it it consisted of dry cells; (b) if it was a lead-acid storage battery; (c) if it was an Air-cell battery?
8. A receiver employs three '32 type tubes as r-f amplifiers, one type '30 tube as a detector and two '33 type tubes in push-pull. The detector plate voltage is 45 volts and that applied to the amplifier tubes is 135 volts. Proper grid-bias voltages are applied to each. What is the total current drawn from the "B" batteries? (Use the table in Fig. 214.)
9. What is the total filament current drain of the above receiver?
10. What are the advantages of arranging the circuit of a battery operated receiver so self-gridbias voltage is provided, instead of using dry cell "C" batteries? What are the disadvantages?
11. Why is the total voltage amplification produced in a radio receiver calculated by *multiplying* together the amplifications produced by the individual stages, rather than *adding* them?

CHAPTER 27

THE POWER SUPPLY UNIT

ELIMINATING THE "B" BATTERY — TYPES OF SUPPLY LINES — REQUIREMENTS OF THE B POWER SUPPLY UNIT — B POWER UNIT SYSTEM — POWER TRANSFORMER — RECTIFIERS — HALF-WAVE RECTIFIER — FULL-WAVE RECTIFICATION WITH HALF-WAVE RECTIFIER TUBES — FULL-WAVE RECTIFIER TUBE — MERCURY VAPOR RECTIFIER TUBE — THE FILTER SYSTEM — TUNED CHOKE FILTER SYSTEM — FILTER SYSTEM ARRANGEMENTS — THE CHOKES AND FILTER CONDENSERS — VOLTAGE DIVIDER SYSTEMS — VOLTAGE DIVIDER WITH VARIABLE RESISTORS — VOLTAGE REGULATION — LINE DISTURBANCES — COMPLETE POWER SUPPLY UNIT — "B" POWER SUPPLY UNIT FOR D-C LINES — MEASURING OUTPUT VOLTAGES — REVIEW QUESTIONS.

496. Eliminating the "B" battery: In the battery-operated receivers considered in the previous chapter, common dry cell "B" batteries are used as a source of voltage for maintaining the plate of each tube at a positive potential with respect to its cathode. The filament current is also furnished by a battery. While receivers of this type do have certain fields of application as pointed out, they form a small portion of the receivers in use, because of the troublesome necessity for battery renewal and the fact that the use of sufficient "B" batteries for obtaining the high plate voltages for the proper operation of modern power tubes having adequate handling capacity, is very expensive and impractical. Wherever either a. c. or d. c. electric light service mains are available, it is much more satisfactory and economical to obtain all "A", "B" and "C" power for the operation of the receiver, from the electric light mains. Receivers operating this way are called *electric receivers.*

As has already been pointed out, the purpose of the filament current is merely to heat the cathode to a temperature at which electrons are emitted. Any form of current will heat a filament, so either direct or alternating current may be used for this purpose. The problem of filament current supply in electric receivers is solved satisfactorily by using separate-heater type tubes, whose filaments are heated by either the direct current or raw alternating current of proper voltage from the electric light lines. The problem of plate voltage supply is not so simple, because the plate voltage applied to the tubes must be unidirectional and absolutely steady with no pulsations. Any rapid variations or pulsations in the B supply voltage will cause corresponding variations in the plate currents of the tubes, in exactly the same way that the radio signals do. These, being amplified by each successive tube, will be quite strong at the

output of the receiver and will cause objectionable loud hums or other noises to be heard in the loud speaker. Just how important this is, may be seen from the following experiment:

Experiment: Obtain a complete receiver and loudspeaker, which are capable of good low note reproduction. The receiver should preferably be of the battery operated type to facilitate changeover of connections, and a 1 mfd. condenser should be connected in series with the ground lead between the ground terminal on the receiver and the ground connection. Operate it so a station is received loudly and clearly. Now disconnect the B batteries and connect the 110 volt a-c electric light circuit in their place, all the B+ terminals of the set going to one side of the lighting circuit, and the B— terminal going to the other side. Nothing but a loud 60 cycle hum or roar will now be heard. If a d-c electric light circuit is available, this may be used instead of the a-c line, being careful to connect the positive side of the line to the B+ terminals of the receiver. In this case the hum will not be so loud, but it is enough to be objectionable.

This experiment convincingly illustrates the fact that the voltage in the form supplied by the electric light supply line is not suitable for use directly as the plate voltage in the radio receiver. It can be made suitable however, by proper apparatus which we will now study. That for use with a-c electric light lines will be studied first. The apparatus for use with d-c lines is much simpler and will be studied later.

497. Types of supply lines: Current for electric lighting and power purposes is supplied in two forms, *alternating current* and *direct current*. The use of a-c for this purpose is the most common and widespread, although many communities are supplied with d-c. The construction of the "B" power unit depends upon the type of current supplied. This may be ascertained in any particular case by inspecting the nameplate on the watthour meter installed by the electric light company for measuring the amount of power consumed, or by communicating with the local electric light company. We will first consider those "B" power supply units which are designed for operating the plate circuits of radio receivers from the a-c electric light circuit.

498. Requirements of the "B" power supply unit: Before proceeding with the actual study of the operation and construction of the "B" power supply unit, it is well to understand just what must be accomplished by it. We will assume that the electric light circuit is of the ordinary type delivering a voltage of 110 volts alternating at a frequency of 60 cycles. If other voltages or frequencies are supplied, only minor changes in the construction of the parts is necessary, the main system remains essentially the same. The voltages supplied by the unit to the plate circuits of the tubes in the receiver must be steady, non-pulsating, and always in one direction so that the plates of the tubes are always maintained positive with respect to the cathodes. This is necessary for proper tube operation. For this reason, the alternating voltages cannot be applied directly to the receiver, the "B" power unit must "rectify" or change them to direct voltages. The voltages must be non-pulsating, because even a small fluctuation in plate voltage will cause a fluctuation in the plate current of each tube. This will be amplified by the receiver and become large enough to produce an objectionable low-pitched hum from

the loud speaker. Therefore the "B" power unit must also smooth out all ripples in the voltage. Since these modern receivers employ at least two types of tubes, (general purpose amplifier tubes and power amplifier tubes) which require different values of plate voltage, it must be capable of delivering the various plate voltage values required. Since these voltages are generally higher than the 110 volts supplied by the electric light line (see Fig. 214), the "B" power unit must also be capable of stepping up the line voltage to the required value, depending on the particular types of tubes employed in the receiver. Also it must be capable of supplying the total plate current required by the various tubes, without undue heating or voltage drop.

499. "B" power unit system: A study of these requirements shows that a "B" power supply system must do several things. It must step up the 110 volt a-c line voltage to the higher "plate" voltages necessary for the

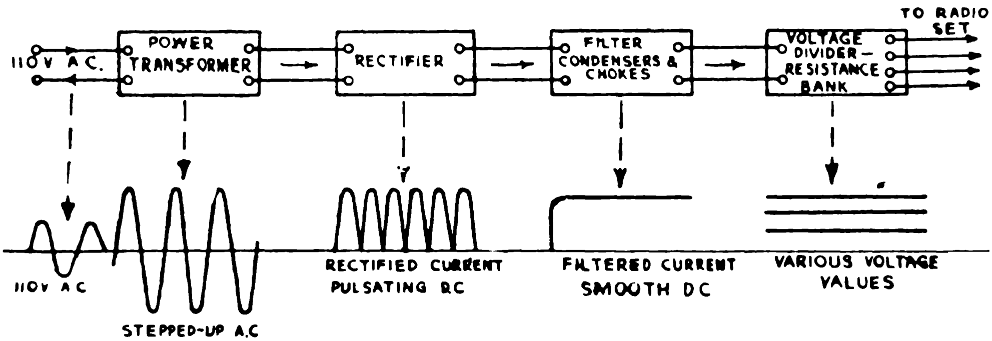


Fig 368—The main parts of a "B" power supply unit are shown here in the order in which they occur. The changes which the current and voltage undergo and the various forms in which they are present in these parts, are shown by the graphs below

proper operation of the various tubes used in the receiver, it must rectify the a-c to d-c, it must smooth out the resulting pulsating d-c, and it must provide some means for obtaining several intermediate voltages for the different types of tubes. These functions are performed by the four main parts of the unit, which are as follows:

(1) *Power transformer*: Steps up 110 volts of the line to higher voltage.

(2) *Rectifier*: Changes the a-c from the line to pulsating d-c.

(3) *Filter*: Changes the pulsating d-c output of the rectifier, to smooth d-c.

(4) *Voltage divider*: Enables various voltages to be obtained for the plate circuits of the various tubes in the receiver

These main parts are shown in the block diagram of Fig. 368, in their proper sequence from left to right. The form of voltage or current which

exists in each part is shown graphically in the lower part of the diagram We will now study the operation of each part in order, starting with the voltage step-up in the *power transformer.*

500. The power transformer: The *power transformer* contains a primary winding and several secondary windings—all on a laminated steel core. One secondary winding contains more turns than the primary. Its purpose is to deliver the high voltage which is to be rectified and used for the plate circuits of the tubes. Another low voltage winding of a few turns supplies heating current for the filament of the rectifier tube which will be described. These are the only windings employed for the "B" power pack, but since low-voltage alternating current is also needed for the heating of the filaments of the detector and amplifier tubes in the receiver, this is conveniently obtained by placing one or more additional low voltage windings on the core of the power transformer to supply this current. In this way a single transformer is used to furnish all filament and plate voltage for the filament current supply and another one for plate voltage supply. This reduces the cost and makes the receiver more compact and light. A typical power transformer of this type is shown at the left of Fig. 72. The various windings on the center leg of the core are plainly visible. Typical connections of the various windings may be seen in the circuit diagram of Figs. 282 and 283. The power transformer should be designed with ample copper and iron so that the secondary voltages remain practically constant even though the electric light line voltage varies slightly at different times. It should also be of ample size to supply the required power without undue heating.

501. The rectifier: The next important part of the system is the rectifier tube which changes the high voltage a-c delivered by one secondary winding of the transformer, to pulsating d-c. When an alternating voltage is applied to it, it allows the current to flow in one direction only, by offering a very high resistance to the flow of current in the opposite direction. Rectifiers are divided into two types, half-wave and full-wave. In *half-wave* rectification, only one part of the current wave is utilized, the flow of current being stopped during each half cycle. In *full-wave* rectification the circuit is so arranged that both halves of the waves are utilized. Two half-wave tubes can be connected to form a full-wave rectifier. While there are several types of rectifying devices such as the electrolytic rectifier, the dry plate rectifier, etc., available for the purpose, vacuum tubes are used almost exclusively in B power supply units, on account of their long life, low cost, and general suitability for the purpose. There are two general types of vacuum tube rectifiers. These are, the *cold cathode* type and the *hot cathode* type. The former is the gaseous type of rectifier, which was very popular at one time, and was marketed under the name of "Raytheon Tube". This employed helium gas. Since these tubes are no longer manufactured in quantity, or used generally, we need not consider them. The hot cathode form of rectifier tube in-

cludes the common vacuum type rectifier tube used widely and the mercury-vapor rectifier which presents several advantages over the other types and is used in the high-voltage rectifier systems of public-address equipment, radio transmitters, and also in some broadcast receivers. The different types of rectifiers may be employed according to the requirements of the equipment with which they are to be connected.

502. The half-wave rectifier: Mention was made in a previous chapter of the early form of vacuum tube containing only an electron-emitting filament and a plate. This two-electrode form of tube forms the basis of half-wave rectifier tubes. The '81 type of tube of this form consists of a double V-shaped filament and a single surrounding metallic plate sealed

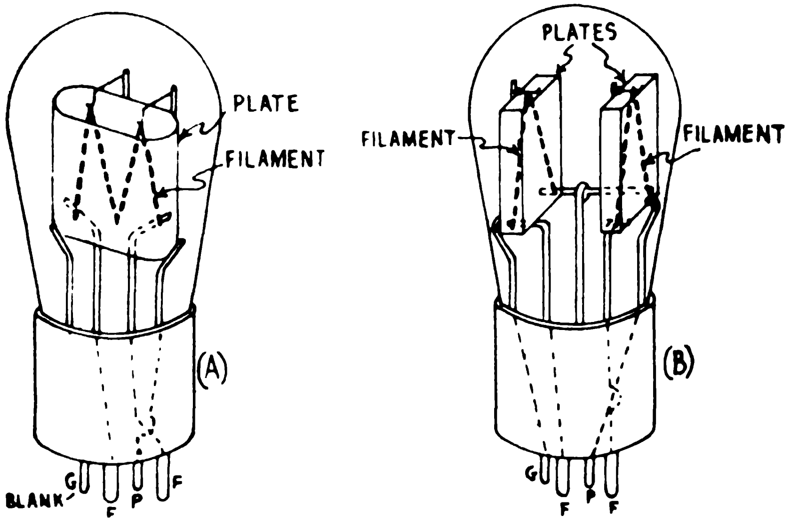


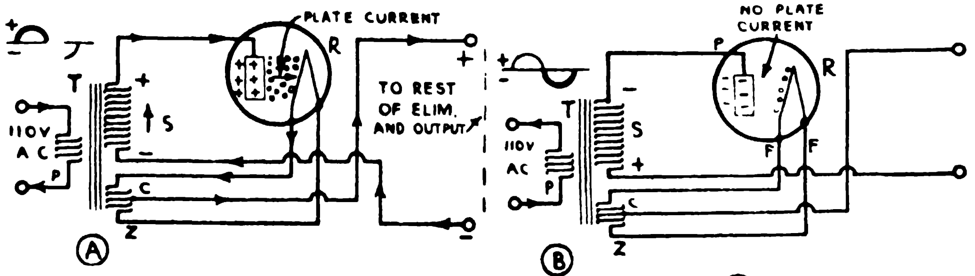
Fig. 369—(A) How the double-hairpin shaped filament and single plate are arranged in the '81 type half-wave rectifier tube
(B) How the two single hairpin filaments and two plates are arranged in the '80 type full-wave rectifier tube. The two filaments are connected in series inside of the tube

into a bulb from which the air has been thoroughly pumped out. The filament is of the oxide-coated thick-ribbon type designed to emit a liberal supply of electrons. The arrangement of the elements is shown at (A) of Fig. 369. The two ends of the filament connect to the usual two thick "filament" prongs in the 4-prong base, and the plate connects to the usual "plate" prong. The fourth prong is a dummy—having no connections—and is placed on the tube merely to help hold it firmly against the socket contacts.

The connections of the tube to the power transformer are shown in Fig. 370. The filament is heated by low voltage (7½ volts) alternating current from the secondary winding "Z", so it emits electrons freely. The high plate voltage (about 700 volts effective value for an '81 type tube) is supplied by the winding "S". As the transformer operates on a-c, the polarity of the terminals of the winding S reverses during each half cycle. The diagram at (A) shows the conditions when the top terminal of

winding S is positive and the bottom terminal is negative. This makes the plate of the rectifier positive, and it attracts the electrons emitted by the filament. The plate current then flows from plate to filament, through half of winding Z to the center-tap C (or to one end of the winding), and out to the rest of the "B" power unit and the plate circuits of the tubes being operated, back through the minus terminal of the "B" power unit to the lower terminal of S, making a complete circuit. The direction of the current is shown by the arrows.

On the next half cycle as shown at (B), the polarity of S reverses, the top terminal now being negative. As this is connected to the plate it makes the plate negative, thus repelling and stopping the flow of electrons, and no current flows through the rectifier. This half of the wave is thus eliminated. Therefore the current flows in the external circuit in one direction only, one spurt of current getting through the tube during the half of each cycle when the plate is positive. At (C) the half-wave rectifier effect is shown. At the left is the form of the a-c voltage applied to the primary of the power transformer and also that delivered by the secondary winding



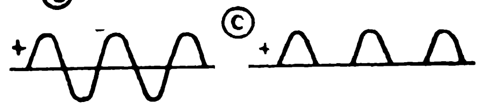


Fig 370—(A) The operation of the half-wave rectifier Current flows from the plate to the filament only during each half of the a-c cycle when the plate becomes positive with respect to the filament.

(B) The plate is now negative. It repels the emitted electrons, and therefore no plate current flows

(C) The a-c line current and the half-wave rectified current.

to the tube. At the right is the pulsating d-c rectified voltage and current appearing in the output circuit of the rectifier tube.

Notice that if a 60 cycle voltage is applied to a half-wave rectifier, since current flows through the rectifier once for each cycle, the output voltage is unidirectional and has 60 pulsations per second.

Notice that this current stops flowing entirely during half of each cycle. This makes it rather difficult to completely filter and smooth the current output of a half-wave rectifier, since the filter must actually store enough current during the peaks of each current flow to be able to keep current flowing in the external circuit during the entire intervals when no current flows through the rectifier. Actually it must store even more than this to completely smooth out the ripples.

For this reason, half-wave rectifiers are not employed extensively in any applications for which a suitable full-wave rectifier tube is available, because the cost of the filter system necessary to completely smooth out the output current of a half-wave rectifier is much greater than that of a filter system designed to smooth out the less pulsating output of a full-wave rectifier tube. Half-wave rectifiers of the '81 type may be built sat-

isfactorily to handle higher voltages than those handled by the '80 full-wave type, so they are particularly useful for supplying the high plate voltages required for the large power tubes of the '50 type, etc., used in public address systems, etc. It is entirely practical and common however, to connect two half-wave rectifier tubes in a suitable circuit to obtain full-wave rectification as we shall now see. In this way all of the advantages of full wave rectification are retained together with the high-voltage handling capabilities of the half-wave rectifier tube.

503. Full-wave rectification with half-wave rectifier tubes: If two half-wave rectifier tubes are connected as shown at (A) of Fig. 371, full-wave rectification is obtained.

The filaments of the two tubes are connected in series across the low voltage heater winding Z, of the power transformer The high voltage secondary winding S, has its end terminals T and W connected to the plates of the rectifiers as shown.

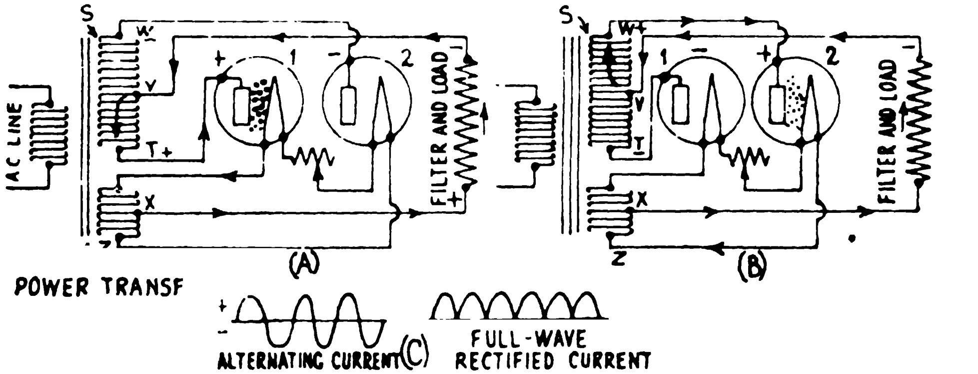


Fig 371—How two half-wave rectifier tubes may be connected to obtain full-wave rectification Each tube allows current to flow through it from plate to filament during alternate half cycles The full-wave rectified current shown at (C) results This system is used extensively in high voltage power supply units for sound amplifier and public address systems

It also has a center tap V on the winding, which connects to the filter circuit and load, represented simply by the resistance symbol. This circuit returns to the center tap on the filament heater winding Z. Since an a-c voltage is generated in winding S, the potential of its end terminals alternates during each half cycle. At one instant the bottom terminal T, will be positive with respect to the top terminal W, as shown. The potential of the center tap V is midway between these two, i.e., it is negative with respect to T and positive with respect to W. Therefore since this center tap returns eventually to the filament circuit of the rectifier tubes, at the instant pictured in the diagram, terminal T and the plate of tube No. 1 are positive with respect to the filament of this tube, so the electrons are attracted to the plate and a plate current flows from the plate to the filament, down to point X, and out through the filter system and load in the direction of the arrows, coming back to point V and thus completing the circuit. During this time, terminal W and plate of tube No. 2 are negative with respect to the center tap V and the filament, so no current flows through this tube. On the following half cycle, the polarity of the terminals of winding S reverses, and becomes as shown at (B). Terminal W and the plate of tube No. 2 are now positive with respect to the center tap V and the filament of the tube. Therefore, the plate attracts the electrons from the filament, and a current flows from the plate to point X and around through the circuit in the direction shown by the arrows. Tube No 1 is now inactive since its plate is negative with respect to the

filament. During the following half cycle it becomes active again and the current flows through it, tube No. 2 becoming inactive. The effect then, is for each tube to become operative during one half of each cycle, passing current through from plate to the filament, and around through the external circuit. First one tube operates and then the next. Notice that the current flows through the external load circuit in the same direction no matter which tube is operating, so that the output current is a *direct current*, pulsating as shown at the right of (C).

It is evident that the full-wave rectified current at (C) flows through the external circuit during each half cycle. Comparing this with the half-wave rectified current at (C) of Fig. 370, it is evident that it is much easier to smooth out than the latter, since the filter need only return current back to the line during the short periods when the full-wave rectified current drops to zero value, during each half cycle. Consequently, the filter apparatus is much simpler and cheaper as we shall see later. This is the important advantage of full-wave rectification.

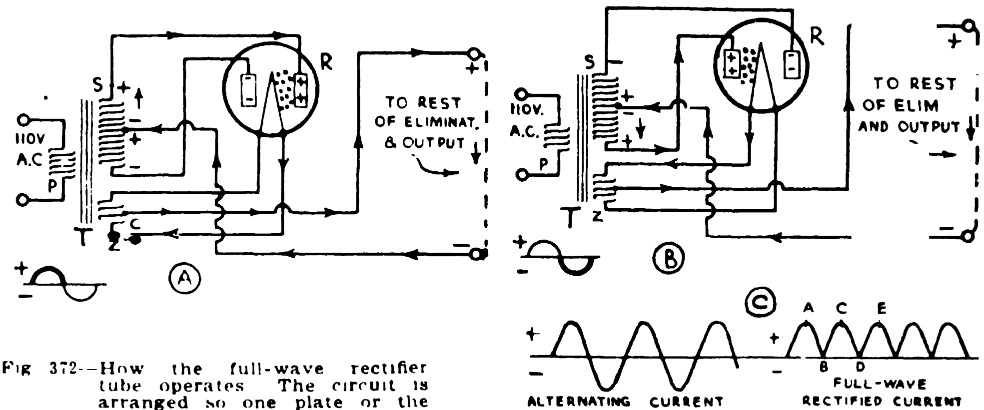


Fig 372—How the full-wave rectifier tube operates The circuit is arranged so one plate or the other is positive during each half cycle and is therefore allowing current to flow through to the filament circuit, which becomes the positive side of the output circuit

504. The full-wave rectifier tube: A single tube which performs the function of full-wave rectification which was accomplished by the two half-wave rectifier tubes in Fig. 371, is known as a *full-wave rectifier tube.* The vacuum type full-wave rectifier tube, consists of two separate plates. Each plate encloses a V-shaped oxide-coated, thick ribbon filament as shown at (B) of Fig. 369. The two filaments are connected in series inside the tube, and in the typical '80 type full-wave rectifier used extensively in electric radio receivers, the entire filament is designed to be heated by a 5 volt source of voltage (see Fig. 214). Since there are two filament terminals and two separate plate terminals, a 4-prong base is employed with the terminal arrangements as shown. The connections of a tube of this type to the power transformer are shown in Fig. 372. The filament is heated by alternating current at 5 volts supplied by the heater winding Z. Each plate is connected to a terminal of the high voltage winding S. The center-tap on this winding connects to the filter and load circuit as shown, the circuit returning to a point in the fila

ment circuit. This point may be either a center-tap on the filament winding as shown, or it may be one end of the winding, no appreciable difference resulting from either connection. The latter is the cheapest arrangement since it eliminates the cost of making the center-tap.

The action of this circuit is exactly similar to that described in Article 503 for the two half-wave rectifier tubes, excepting that the two plates and two filaments are placed together in one tube instead of two separate tubes. This will be now reviewed briefly, referring to the typical full-wave rectifier circuit shown in Fig. 372.

On the positive half of the a-c cycle, the upper terminal of winding S is positive thus making the right-hand plate positive. The lower terminal of S and the left-hand plate are negative. The center tap on S is at a potential half way between these two; it is negative with respect to the upper terminal and positive with respect to the lower terminal. Since the right-hand plate is positive with respect to the center-tap and the filament, it attracts the electrons emitted by the filament. Therefore, a current flows from it to the filament, through half of the filament winding as shown, and out of the center tap to the positive output terminal, through the external filter and load circuit, and back to the negative terminal to the center tap of S. The left-hand plate, being negative, takes no part in the action. Notice that only the upper half of winding S was effective during this period and, therefore, the effective voltage acting on the rectifier tube is half of the total voltage of winding S.

On the next half cycle, the polarity of S reverses and the left-hand plate becomes positive as shown at (B). A current flows from this plate to the filament and around through the circuit as shown. The right-hand plate, being negative, takes no part in the action. Notice that the direction of the current in the external circuit is exactly the same as at (A), so the eliminator delivers a direct current. The wave-form of the applied a-c voltage and that of the rectified output are shown at (C). Notice that both halves of each a-c cycle have been utilized, and the rectified current is much smoother than that produced by a half-wave rectifier and therefore much easier to filter and smooth out completely.

505. Mercury vapor rectifier tube: The development of the hot-cathode type mercury vapor tube rectifier, has been brought about by the demand for a rectifier having a low plate-filament resistance and therefore a low internal voltage drop and high efficiency. The '66 type rectifier (see Fig. 214) is typical of this type of tube. The half-wave type has an oxide-coated filament in inverted "V" form. The plate is suspended horizontally above it and has a disk shape. It connects to a small cap on top of the bulb for external connection. Mercury is introduced into the tube during the time of manufacture. When the filament is heated, a cloud of mercury vapor or free gas atoms of mercury are formed from this. Electrons are also liberated from the heated filament in the usual manner, which, under the influence of a plate potential, collide with the mercury vapor atoms in the space between the filament and plate, to produce ionization of the mercury. This ionization liberates a large number of free electrons from the mercury atoms, in the space between the plate and filament. Since these are immediately attracted by the plate, this increases the current flowing between the plate and filament. Consequently, this type of tube can be built to handle much more current than the ordinary vacuum types. The ionization produced in the tube, produces a characteristic blue glow in it during operation. Due to the presence of the mercury vapor, the resistance of the plate-filament path is low, and is

constant over a wide range of load current. This is a true mercury vapor drop, and is generally about 17 volts. Consequently, the loss of energy in the tube itself is very low and the heating of the plate is low. This type of tube is made in several ratings and is capable of handling high voltages and rather large currents, with very little voltage drop and high efficiency. Rectifier tubes are rated on the basis of the peak inverse plate potential and the peak plate current values which they can stand. The maximum *peak inverse plate potential* rating of a rectifier tube is the highest potential the tube will stand in a direction opposite to that in which it is designed to pass current, without danger of internal arcing and short-circuit between the elements. The *maximum peak plate current* of any vacuum tube is the highest peak current that it can stand in the direction in which it is designed to pass current.

In the full-wave type of mercury vapor rectifier tube, two plates and two filaments are used, exactly the same as in the common type '80 vacuum tube rectifier. An idea of the increase in current capacity which is obtained by employing the mercury vapor principle may be gained from the fact that while an '80 vacuum type full-wave rectifier is rated at 400 volts r. m. s. a-c voltage per plate and 120 milliamperes maximum output, a mercury vapor type rectifier of similar construction and size is rated at 500 volts and 300 milliamperes!

506. The filter system: Now that we have seen how the a-c line voltage may be stepped up to any required value by the power transformer, and how the a-c current may be rectified, by either a half-wave or full-wave rectifier of either the vacuum or the mercury vapor type, let us study the operation of the typical filter circuit which smoothes out the pulsating direct current delivered by the rectifier. Examination of (C) of Fig. 372 shows that the output current from the rectifier is a pulsating direct current which increases from zero to maximum value at A, decreases again to zero at B, increases to maximum at C, decreases to zero at D, etc. Any device, which, when connected in the output circuit will store current during the peak-current instants A, C and E, etc., and deliver it back to the circuit during the instants B, D, etc., when the current delivered by the rectifier is low, will serve to smooth out, (*or filter*) the current. Such a device used in a "B" power unit is commonly called the *filter*. Since a condenser has the property of storing electrons or current when a potential difference is applied to its plates, and releases them when the applied potential difference of the circuit becomes less than the potential of the plates, it is natural that condensers should be used for performing this function of smoothing the current flow. They are assisted in their action by iron-core choke or inductance coils (see (C) of Fig. 75) connected properly in the filter circuit. These chokes are wound with a great many turns of wire on steel cores, thus possessing high inductance. They therefore have the characteristic property of an inductance, i.e., they oppose any change in the current flow through them, whether this change be an increase or a decrease in current (Lenz's Law).

A typical full-wave "B" power supply unit circuit with its *brute-force* type filter, is shown in Fig. 373. While several variations of this circuit are possible, it will serve our purposes best for study of the fundamental filter actions, since when its action is understood, the operation of any filter circuits will become clear, because they vary only in minor details. The action is as follows:

The alternating current power transformer steps the 110 volt a-c line voltage up to the high voltage shown at A, which is applied to the plates of the tube. Also, as soon as current is supplied to the primary of the power transformer, the twin filaments in the full-wave rectifier tube heat up. Plate current starts to flow first from one plate to the filament and then from the other, so that the center-tap of the filament-heating winding is always positive with respect to the center-tap of the high-voltage winding. Since the potential difference is being applied across the condenser B, it charges up. Let us start at the instant when the output current and voltage of the rectifier are beginning to increase from zero to maximum (B to C at (C) of Fig. 372). On account of its high inductance (30 henries or so), choke coil F opposes the flow of this increasing current out to the external circuit, and so helps condenser B which is across the circuit, to store a charge of current or electrons into its plates, becoming charged to a potential equal to the peak value. Now the current from the rectifier begins to decrease, (C to D at (C) of Fig. 372). The choke F, by its self- induction action, tends to prevent the current from decreasing (see Article 115), and at the same time, condenser B now being charged to a higher potential difference than that existing across the line, discharges its excess current or electrons. It cannot discharge through the path back through the tube from filament to plate, because current cannot flow in a vacuum tube from filament to plate. It does however, discharge out through choke F and into the external circuit, and so maintains the flow of current through the external circuit even though the rectifier is not supplying much during this time. The result is, that while the current flowing through the rectifier drops to zero during each half cycle as shown at B of Fig. 373, the combined action of the filter condenser and choke keep the current flowing in the external circuit during these instants, as shown by the solid-line curve at C.

The first condenser B can be considered as a voltage regulator insofar as it absorbs each current pulsation in taking a charge from the rectifier output, and feeds the current back to the line when the voltage drops. The charge is absorbed at the peak, thus helping to fill in the valley between the peaks. The first choke coil F opposes the rapid building up of the current as it rises to a peak, by the building up of a counter-electromotive force. As the current reaches its highest value, and begins to decrease, the energy which has been stored in the magnetic field of the coil by the increasing current is now fed back into the circuit. If the current is not smoothed sufficiently by the first choke and condenser of the filter, a second section C-G may be included. In this, the same operation is carried on a second time, but the current on which it operates has had its pulsations smoothed out to a great extent before entering it, and is very much more smooth when it leaves it. The current that passes out of the second choke is usually a very smooth direct current, as shown at D, and the output voltage is sufficiently smooth and steady to be used for the plate circuit supply of a radio receiver.

The third condenser D normally floats across the line in a charged condition, since the voltage across it is practically non-pulsating. However, if a powerful signal or a loud low-frequency note is suddenly received and amplified by the radio receiver, the plate current flowing in the plate circuits of the tubes in the receiver will suddenly increase. Thus increase in the plate current flowing through the circuit of the "B"

power supply unit causes the individual I $\times$ R "voltage-drops" in the power transformer windings, rectifier tube, choke-coils, etc., to increase. This would result in a momentary drop in the output voltage of the "B" power supply unit if it were not for the fact that the last condenser D, having been charged to the higher normal voltage, now discharges some of its current back into the line and thus meets the demand for the momentarily increased plate current drain. In this way, this last condenser acts as a reserve current storage device, and keeps the output voltage steady. In some cases, it must be of large capacity (3 to 10 mfd.), if good low-note reproduction is to be obtained. Thus, condenser B controls voltage regulation, C controls hum elimination, and D controls current storage for good quality of low-frequency note reproduction.

It is not always necessary to use two choke coils in the filter system.

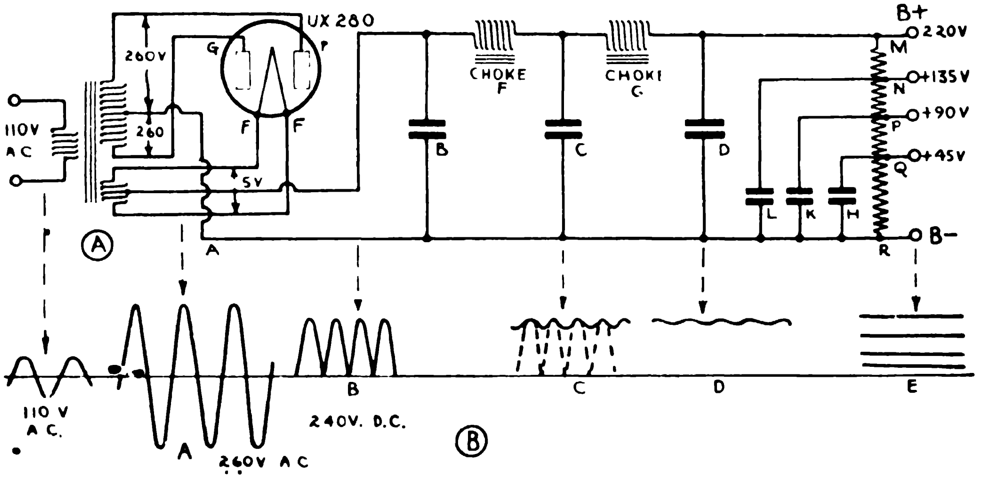


Fig 373- Complete full-wave "B" power supply unit with 2-section filter The wave-forms of the currents and voltages existing in the various main parts are shown below Note that the input is a-c The output is smooth d-c at various voltages

In many commercial receivers, the second choke G and condenser D are omitted, the single choke with its two condensers being sufficient to smooth out the current and voltage to the value required for hum-free operation. Also, in many commercial receivers the field coil of the electro-dynamic loud speaker used in the receiver is used as a choke coil in the filter system, as shown at the left of Fig. 344, since it possesses a high inductance. In many cases, especially in midget type receivers, where cost and space are important, the speaker field is the only choke employed. The B current flowing through it serves a useful purpose in energizing the field of the speaker. (Other field connections for the electro-dynamic speakers are shown in Fig. 274). Also, it is not necessary to connect the choke in the positive side of the line as shown in Fig. 373. So far as the filter action is concerned, it may be connected equally as well in the negative side. Many receivers have the choke connected this way, employing the voltage drop in the choke or a part of the choke winding, as a source of C-bias voltage for tubes in the receiver. The receiver circuit of Fig. 282 shows the connection of the field coil (L-11) of the speaker in the

negative side of the circuit, as the only choke in the B power supply unit.

Any degree of filtering action may be obtained by using filter condensers of larger capacity and using chokes of larger inductance. However, as the larger chokes and condensers are more expensive, receiver manufacturers use the smallest chokes and the least amount of condenser capacity, that will give satisfactory filter action and even resort to special filter circuit arrangements which improve the filter action so that cheaper chokes and condensers may be used. Although tinfoil-paper type filter condensers are used in filter circuits, (see Articles 138 to 144) the use of dry electrolytic condensers is more widespread on account of their lower cost per mfd., and their more compact form (see Articles 144 to 150). The forms of condensers shown in Fig. 96 are very desirable for this purpose.

507. Filter system arrangements: Several filter system arrangements are used in radio receivers. While the filtering or smoothing action of each is the same, the circuits are arranged somewhat differently in an effort to cheapen the chokes and condensers required. In some systems, the circuit is arranged so as to provide also, the correct C bias voltage for the tubes in the last audio stage of the receiver.

At (A) of Fig. 374, a simple filter in which two chokes or inductances L_1 and L_2, and three filter condensers are employed is shown. In most cases, the field coil of the electro-dynamic loud speaker used with the receiver acts as the second choke L_2, (see Article 460). In this way, it obtains its proper energizing current, and at the same time, serves a useful purpose as a choke in the filter. When a 2-choke system of this kind is used, the plate voltage for the tubes in the last audio stage of the receiver is taken off by tapping the circuit ahead of the last choke, as shown.

This is done to supply a higher voltage to these tubes, since the voltage drop through the last choke is not included. Also, it reduces the direct current flow through the second choke, and thereby lessens the steady field in it. This means that since the tendency of the core to saturate is reduced, the choke may be made smaller and cheaper for a given inductance value. Also, any plate circuit coupling which might exist between the last audio stage and other tubes in the receiver, due to the common heavy plate current flowing through the impedance of the chokes, is reduced, since the second choke is eliminated from the circuit of the last audio tubes by this method. It is true that the plate voltage and current supplied to the last audio tube will not be filtered as well. This is not objectionable, since some plate current ripple can be tolerated here because there are no following tubes to amplify any slight hum voltage which may be set up across the plate load. In general, the plate current supplied to the power output tube in the receiver requires very little filtering, the first a-f and r-f amplifier tubes require more, and the detector tube requires most.

At (B) a filter arrangement in which but a single choke coil and two filter condensers are used, is shown. Usually the electro-dynamic speaker field of the receiver is used as the choke coil. Notice that the first filter condenser is of larger capacitance than the usual first filter condenser used in the 2-choke system. This is necessary in order to secure adequate filtering action. This system is used most in midget-type receivers, since it reduces the cost of the filter, and considerable space is saved in the chassis since no choke other than the speaker field winding is needed. Dry-

electrolytic type filter condensers (see Fig. 96) are usually employed on account of their low cost per mf., and small physical dimensions.

At (C) a *tuned choke* filter system is shown. The choke L contains two windings wound or connected so their magnetic fields oppose each other. The inductance L and the condenser C_2, form a resonant circuit of low impedance, which effectively eliminates the ripples in the current, provided the circuit is so designed that resonance is produced at the frequency at which the ripples occur. The advantage of this circuit is that a small low-cost choke and fairly low values of capacitance gives good filtering action.

At (D), the Miessner *tapped-choke system* is shown. Here, the rectifier is connected to the filter choke by a tap at some point near one end,

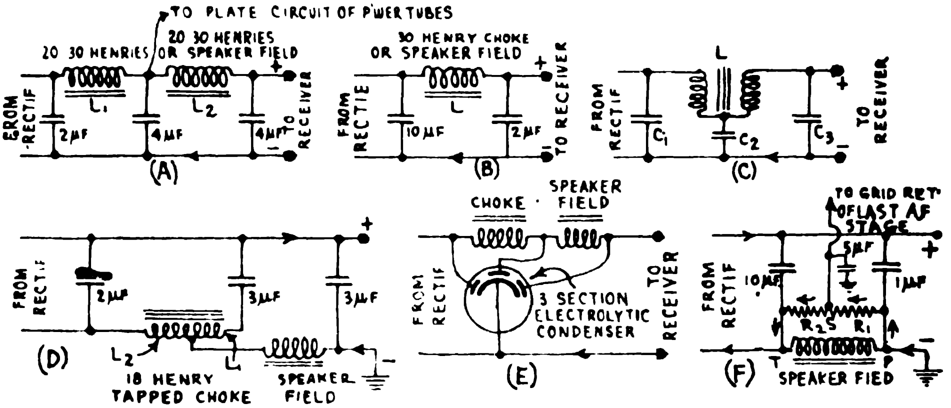


Fig. 374 – Various arrangements of chokes and filter condensers used in the filter systems of power supply units in a-c electric receivers

the filter condensers being connected to the ends of the choke winding. This arrangement reduces the ripple in the current by a factor of five to ten over that obtained with the same choke and condensers connected in the usual manner of (A). Or, conversely, it will provide just as good filtering with considerably smaller values of inductance and capacitance.

The increased filter action is due to a neutralizing effect between the induced a-c components of the two portions of the choke. That is, a rather strong induced a-c component flows through the portion marked L_1, the coupling of which to L_2 neutralizes to a large degree the induced a-c voltage component therein, so that the output pulsations are reduced. A tap located at about 20 per cent from the end (considering the number of turns) is quite effective.

The fact that this system is patented, and is available to receiver manufacturers only on a royalty basis, has perhaps prevented it from being used more extensively, since material savings in the cost of the choke and condensers are obtained by its use. The tapped choke may either be used alone, or another choke (usually the speaker field) may be used with it as shown at (D).

At (E), a common filter circuit with a 3-section electrolytic filter condenser is shown. The common negative terminal of the condenser connects to the negative side of the circuit. Filter condensers of the general type shown at the center of Fig. 96 may be used for this purpose.

At (F), a filter system used in many R. C. A. Victor receivers, is shown. In this the speaker field is used as the choke. Across this are the two resistors R_1 and R_2, properly proportioned so that a negative C-bias voltage of the proper value is obtained by the voltage drop through them. The operation of this interesting arrangement is as follows:

The speaker field acting as a filter choke, is connected in the B- line as shown. The plate-return circuits in the receiver are grounded to the metal chassis which acts as the common B-terminal. The total plate current for the entire receiver returns from the grounded chassis to point P, where it divides in the parallel circuit consisting of the speaker field and resistors R_1 and R_2, as shown by the arrows. The current flowing through each path will be inversely proportional to its resistance. Since current flows from P to S to T, point S is at a lower potential than point P (the grounded chassis) by an amount equal to the voltage drop in resistor R_1. Since the grid return lead of the last audio stage connects to point S, this is thereby maintained at a definite negative potential or grid bias with respect to point P (which connects to the cathode of the tube or tubes in the last audio stage). In this way, by properly proportioning R_1, R_2, and the resistance of the speaker field, the C-bias voltage for the last audio stage is obtained. Resistors R_1 and R_2 may be separate individual units or may simply consist of a single resistor tapped at the proper point.

508. The chokes and filter condensers: The choke coils used in power supply units must have the necessary self-inductance to provide proper filtering in combination with the filter condenser capacities used. The core should be designed with a proper air-gap, to reduce the tendency to saturate due to the steady value of the d-c current flowing through the winding. The use of electro-dynamic speaker fields as choke coils in the filter system is very common. The wire used on the choke should be of sufficient size to safely carry the current continuously without overheating. When the current rating of a choke is exceeded, its inductance decreases rapidly (see Art. 123), and the filtering action is greatly reduced, with consequent increase of hum. The filter condensers may be either of the tinfoil-paper type, (see Figs. 90 to 93), or the electrolytic type. The latter presents the advantages of cheapness, small physical dimensions, and self-healing properties of the dielectric. A single 8 mf. electrolytic condenser and 30 henry choke coil from a B power unit filter system are shown in Fig. 124. These really form a low-pass filter section. An idea of the comparative size of an 8 mf. dry electrolytic condenser and a tinfoil-paper condenser of similar capacitance and voltage rating may be obtained from Fig. 94.

The filter condensers must be built to withstand the *peak* voltages encountered. The condenser nearest the rectifier is subjected to the highest peak voltage. As the voltages at the input of the rectifier and immediately following it are *alternating* and pulsating direct current voltages, respectively, the values usually specified for them are the "*effective values*". The "effective voltage" is the value of voltage which gives exactly the same heating effect as an equal direct current of the same potential. This is the value which an a-c voltmeter indicates. The peak value of an alternating voltage is the maximum value to which the voltage rises during any part of the cycle. Assuming that the output of the rectifier is of sine-wave form, the peak voltage

is 1.41 times the effective voltage. As the insulation of the filter condenser immediately following the rectifier must safely stand the peak voltage twice during each cycle, the condenser used must have a voltage rating exceeding the peak voltage, for safety.

(Note: The relation between "peak" voltage and effective voltage is explained in detail in Art. 107.)

509. The voltage divider: If only one value of plate voltage were required by all of the tubes in a radio receiver, the power supply unit would now be complete, but since the various tubes require different plate voltages, provision must be made to supply them. This is the function of the *voltage divider system.* The fundamental principle involved in all voltage divider systems, is that whenever current is made to flow through a resistance connected in the circuit, a certain amount of the e. m. f. applied to the circuit is used up in forcing the current (or electrons) through the resistance.

The common expression applied to this condition is, that there is a *fall of potential* or *voltage drop* in the resistance. The voltage drop resulting in any case, may be calculated by Ohm's law ($E=I\times R$). Keeping the principle in mind, it is evident that all we need to do to obtain various plate voltages, lower than the maximum voltage appearing at the output terminals of the filter in the power supply unit, is to connect resistances of suitable values in the plate circuits of the various tubes, so that a fall of potential occurs in each, due to the flow of the plate current through it.

510. • Voltage divider systems: Three general connection arrangements are possible for the voltage divider resistors. These will now be studied by means of receiver circuit diagrams in which all of the parts

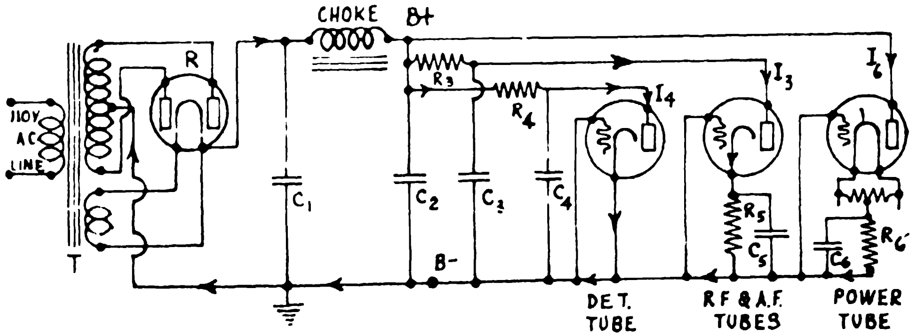


Fig 375—A typical voltage divider system for power supply units. Various voltages are obtained by making the plate currents of the tubes in the radio receiver (shown at the right) flow thru suitable individual resistors in order to produce voltage drops

not entering into the operation of the voltage divider system, have been omitted for simplicity. The detector and amplifier tubes in the receiver are shown with their essential plate circuit and grid circuit connections only, all tuning condensers, transformers, tube couplings, etc. being omitted. The path of the plate current of each tube, is indicated by arrows on the diagrams. The filament circuits are also omitted.

A simple form of voltage divider system is shown in Fig. 375. The typical power transformer T, rectifier R, and single-choke filter system are at the left. The plate circuit of the power tube is connected directly to the high-voltage B+ terminal of the filter ouput. The C-bias voltage is obtained by the voltage drop in resistor R_6. The path of the plate current I_6 is from the B+ terminal, through the plate circuit, through R_6, and back to the B— side of the power unit, as shown. The plate current I_3 for first

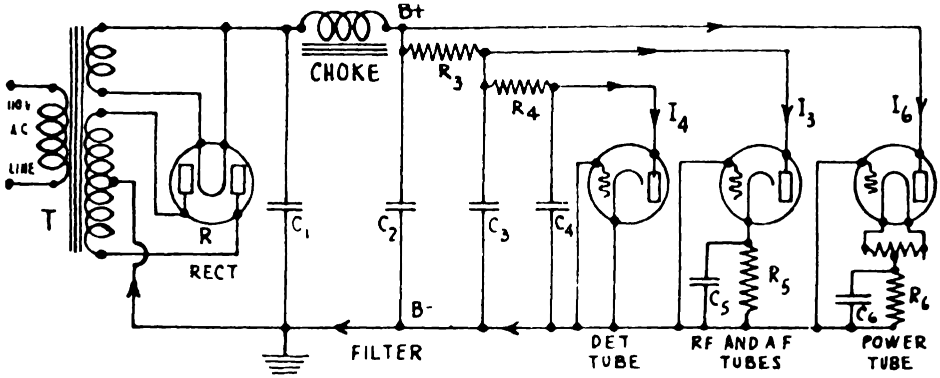


Fig 376—An improved form of voltage divider system for power supply units In this, the detector plate current obtains additional filtering to completely smooth it and reduce hum

a-f tubes, (represented by a single tube in the diagram), flows through resistor R_3 and down through the plate circuit, through C-bias resistor P_5 and back to B—. The plate voltage effective at these tubes, is equal to the maximum voltage output of the power unit minus the $I \times R$ voltage drop in resistor R_3. Suppose the former voltage is 300 volts, the total plate current through R_3 is 20 milliamperes, (.020 amperes), and it is desired to supply a plate voltage of 180 volts to these tubes. Then a voltage drop of $300-180=120$ volts, must occur in the resistor R_3. Its value must therefore be $R=E/I=120/.020=6{,}000$ ohms. In this way, the value of the resistance required to produce any voltage drop may be calculated. By connecting another filter or by-pass condenser C_3 as shown, the resistor R_3 and condenser C_3 act as a resistance-capacity filter, and some additional filtering of the plate current supplied to these tubes, is obtained. The proper plate voltage for the detector tube is obtained by connecting the resistor R_4 in its plate circuit, the actual plate voltage effective on the detector tube being equal to the output voltage of the power unit minus the $I \times R$ voltage drop in resistor R_4. By connecting condenser C_4 as shown, additional filtering of the detector plate current is obtained.

Another voltage divider arrangement which possesses some advantages over this one, is shown in Fig. 376.

As before, the plate circuit of the power tube (or tubes) connects directly to the high voltage B+ output terminal of the filter. The plate voltage for the r-f and 1st a.f tubes is reduced by resistor R_3. It obtains additional smoothing or filtering

from R_3 and C_3 which really form a filter section. The plate current I_4 for the detector tube flows through R_3 and R_4 in series. The condensers C_3 and C_4 act as filter condensers. Therefore, with this arrangement, the detector plate current is really filtered again by a two-section filter, (R_3, C_3 and R_4, C_4), after leaving the main filter of the power unit. Hence the plate current of the detector is filtered more than that of any other tube in the receiver, and is therefore smoother. This is desirable, since the detector tube is more sensitive to disturbing plate current ripples than any other tube in the receiver. These voltage divider systems can be extended to provide any desired plate voltages on any of the tubes in the receiver.

In Fig. 377 (and in Fig. 373) another voltage divider arrangement is shown.

Here a tapped resistor of the general type shown in Figs. 27, 28 and 378 is connected across the "B" power unit output, between points E and H. The resistor contains taps suitably located at points F and G. These divide it into the resistor sections R_1, R_2 and R_3.

The current through the resistor section G-H is I_1 (not marked on the diagram). The current flowing from point E to F is $I_1+I_4+I_3$. Since current I_3 branches off at F, the current in R_2 is, I_1+I_4. As I_4 branches off at G, the current in R_1 is I_1 alone. The plate current I_6 flows directly to the power tube, without entering the resistor. Since the entire resistor is across the output of the filter, a "bleeder" current will flow steadily through it from the positive to the negative terminal. The condensers C_3 and C_4 assist the filtering action, in the same way as explained for the previous system. In order to produce the proper voltage drops in R_1, R_2 and R_3, so that the voltages at F and G are of the desired values for the proper operation of the tubes, these resistance sections must be proportioned carefully.

The following example will illustrate how such a resistor is designed.

Referring to Fig. 377, let I_3 be 20 milliamperes and I_4 be 5 milliamperes. Let the output voltage of the filter, across points E and H be 300 volts. It is desired to apply plate voltages of 180 and 90 volts to the amplifier and detector tubes, respectively (ne-

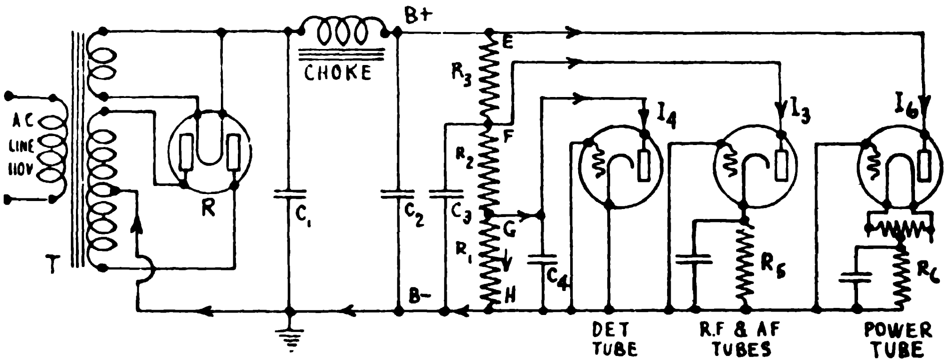


Fig 377—Voltage divider system of the "bleeder resistor" type.

glecting the voltage drop in R_5 and R_6). The "bleeder" current through the entire resistor must be not over 10 milliamperes (this is equal to current I_1).

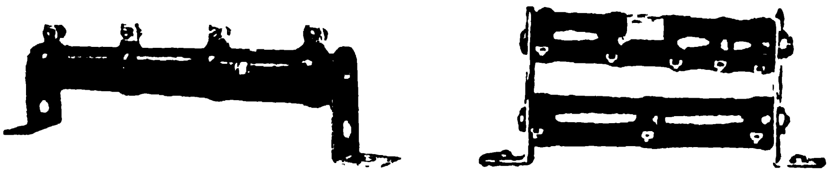
Since 10 milliamperes (.010 amperes) flows through R_1, and point G is at a potential 90 volts higher than point H, resistor R_1 is equal to, $R_1=E/I=90/.010=9{,}000$ ohms. The difference of potential between points F and G is $180-90=90$ volts. This is equal to the fall of potential through R_2. The total current through R_2 is equal to $I_1+I_4=10+5=15$ m.a. Therefore, $R_2=90/.015=6{,}000$ ohms. The difference of po-

tential between point E and F, (voltage drop in R_3), is $300-180=120$ volts. The total current in R_3 is equal to $I_1+I_4+I_3=10+5+20=35$ m.a. Therefore $R_3=120/.035=3{,}400$ ohms. (Approximately.)

It is evident that if exact plate voltages are to be obtained, the voltage divider system in any receiver must be designed especially for the particular number and types of tubes to be operated and the voltages to be applied. Examination of Figs. 376 and 377 shows that the voltage divider in the latter is really the same as in the former, with the exception of R_1. This resistor is called the *bleeder resistor* since it allows the small *bleeder* current to flow through it to the B— minus terminal and back to the rectifier circuit, steadily.

This has one advantage in that it places a small load on the power supply unit almost as soon as the receiver is turned on, since the filament of the rectifier tube heats and begins to emit electrons almost immediately. The separate-heater amplifier tubes do not heat so rapidly, and they may not begin to pass plate current for several seconds. Placing the load on the rectifier immediately, prevents the high-voltage surge produced by the self-inductance action of the high voltage secondary of the power transformer, which would otherwise act on the filter condensers. This therefore lengthens their life. The disadvantage of course, is that the bleeder current flows continuously and places an additional load on the rectifier and the filter. However, by making the resistors of high enough value it may be kept down to a fairly unobjectionable value of 10 or 20 milliamperes.

Although the voltage divider resistors are usually placed near the amplifier tubes in order to shorten the wiring in the receiver, they are properly considered as part of the "B" power unit. The resistors are usually either of the wire-wound type or the solid compressed-carbon type. Several wire-wound resistors suitable for this purpose are shown in Fig. 28. At the left of Fig. 378 is a tapped wire-wound voltage divider resistor of the vit-



Courtesy Ward Leonard Elect Co. *Courtesy Aerovox Wireless Corp*

Fig 378—Left Tapped, wire-wound voltage divider resistor for medium-voltage power supply units
Right 2-section tapped wire-wound voltage divider resistor for high-voltage power supply units

reous enameled type designed for use in power packs delivering medium values of voltage. Its total resistance is approximately 12,000 ohms. At the right is a 2-section tapped, wire-wound resistor used in high voltage power units for public-address systems, etc., in which '81 type rectifier tubes are employed. Its total resistance is about 41,000 ohms. The resistors used should be of proper wattage rating, (I^2R), to safely carry whatever current must flow through them, without undue temperature rise. They should be mounted where they will receive continuous ventilation so that the heat will be carried away as fast as it is developed.

511. Voltage divider with variable resistors: In experimental work, it is often convenient to have a power supply unit having variable resistors in the voltage divider. They may be arranged somewhat as shown at the left of Fig. 379. The 10,000 ohm fixed bleeder resistor is at the bottom. The voltages marked at the taps give some idea of the values which may be obtained from a small unit. Of course, the voltage

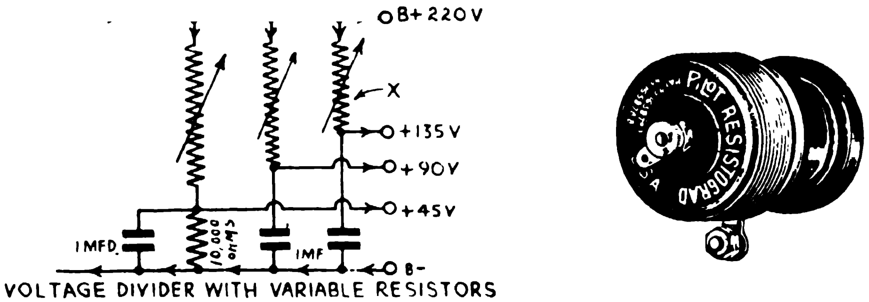


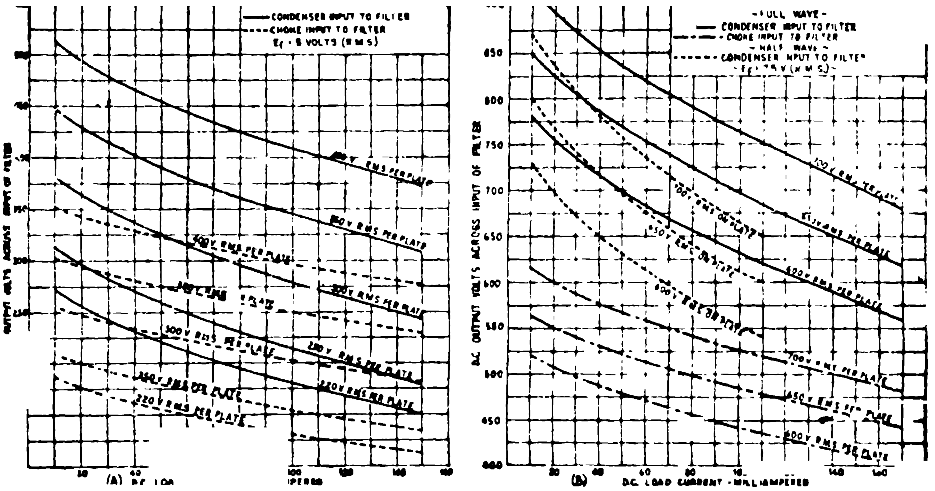
Fig. 379—Left: Voltage divider system with variable resistors. The voltage at each tap may easily be raised or lowered.
Right: A typical powdered-graphite flaked-mica type heavy-duty variable compression resistor for use in the type of voltage divider shown at the left. Its resistance range is from 40 to 10,000,000 ohms.

at each tap may be varied above or below the value marked, simply by varying the resistor in its circuit. A form of heavy-duty variable resistor suitable for this purpose is shown at the right. This is of the powdered-graphite flaked-mica compression type. The case is of metal, with circular cooling-fins to increase the radiation and conduction of the heat developed by the passage of the current through the resistance material.

512. Output-voltage regulation: The current delivered by a "B" power supply unit must flow through the resistance of the high-voltage secondary winding of the power transformer, through the plate-to-filament resistance of the rectifier tube, through the resistances of the chokes, and through the voltage divider resistances. A voltage drop occurs in each of these resistances, proportional to the current flowing. Therefore, the output voltage will not be constant for various values of current drawn from the unit. Of course, no general statement can be made regarding all of these voltage drops since the values of the resistances of the various parts are different in different power units. The voltage drop in the standard types of rectifier tubes can be studied however, by means of the curves shown in Fig. 380. The curves show the voltages existing across the input of the filter for various d-c load currents, when certain fixed values of voltage are applied to the plates of the rectifier tube. The curves at the left are for the '80 type full-wave rectifier tube. Those at the right are for two conditions; one (solid lines), where two '81 type half-wave tubes are connected up in a full-wave rectifier circuit as in Fig. 371; the other (dotted lines), is for a single tube in a half-wave circuit. The curves are drawn

both for the type of circuit in which the rectifier connects directly to the choke coil without any filter condenser between, and for the usual arrangement where the first filter condenser follows the rectifier. Notice, that in all cases, the available output voltage drops as the load is increased.

512A. Line-voltage regulation: In all of those localities where the electric light circuit line-voltages vary considerably from hour to hour, or day to day, the output voltages of the "B" power unit may also vary. In such districts, the voltage is high in the mornings and afternoons when the



Courtesy R C A. Radiotron Co.

Fig. 380—Left. Average output characteristics of '80 type full-wave rectifier tube in typical rectifier circuit
Right Average output characteristics of '81 type half-wave rectifier tube in typical full-wave rectifier circuit

load and the line-voltage "drop" are low. Under this condition, the plate and filament voltages on the tubes in the receiver are high and their life is materially shortened. When the line voltage goes down in the evenings, the tubes do not receive sufficiently high voltages for proper operation. Several devices to reduce this difficulty have been used.

The use of a resistor connected in series with one side of the lighting circuit line has been used extensively because of its simplicity and cheapness.

Typical units of this type, are made in the form shown at the left of Fig. 381. The resistance element is enclosed by the ventilated metal protecting case. The lower end plugs into the lighting circuit socket. The plug from the power supply unit of the radio receiver plugs into the top end. This automatically connects the resistance in series with one side of the line. Some units of this type are made with the resistance easily adjustable to adapt it to the particular requirements of any particular installation. Line-voltage regulators of this type, are only able to reduce the voltage applied to the receiver, down to a certain required value. They are not able to boost the voltage up to this value if the line voltage should fall below normal value.

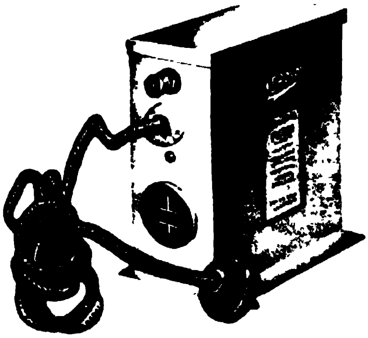
Gas-filled ballast tube voltage regulators, and glow tubes of various kinds, have also been developed for protecting the receiver from harmful rises in line voltage. The ballast lamp is connected in series with the

primary of the power transformer, and consists of an iron filament wire having a high temperature coefficient of resistance, through which the current for the receiver flows.

The filament is enclosed in a glass bulb which contains hydrogen gas. When the line voltage varies, the voltage drop across the tube varies due to its change in resistance, and the voltage effective across the primary of the power transformer remains practically constant. One objection to this form of regulation is that a voltage drop of 40 volts or more occurs in it, and a considerable amount of electrical power is wasted in it in the form of heat. Also, the primary of the power transformer must be wound specially for the 60 or more volts which exist across it, and on which it must operate.

The "glow tube" type of regulator typified by the UX874 type (see Fig. 214) is connected across the 90 volt tap of the voltage divider. It is gas-filled and possesses

Courtesy Ward Leonard Elect. Co.



Courtesy Aerovox Wireless Corp.

Fig. 381—Left A resistance type of line voltage regulator which is plugged in between the receiver power-input plug and the electric light supply socket
Right Typical electric light line "interference eliminator" containing two by-pass condensers having their common junction connected to ground. This connects between the lighting circuit socket and the radio receiver plug

the characteristic such that the voltage across it remains practically constant at 90 volts for all current from 10 to 50 milliamperes.

Several special forms of voltage regulators which operate by magnetic action, have been perfected for keeping the voltage at the receiver terminals constant regardless of whether the line voltage drops or raises above the normal value. While this is the ideal form of voltage regulator, these devices have not found general application in medium priced radio receivers on account of their additional cost. They are used extensively however, in other fields of application where cost is not so important.

513. Line disturbances: In many electric receiver installations, electrical disturbances originate in the electric light supply lines. These enter the power supply unit via the power transformer primary and are transferred to the secondary circuit and thus to the plate supply of the amplifier tubes in the receivers. The reader must have observed the "click" produced in an electric radio receiver, when an electric light switch is turned on or off in the house, and has probably heard the hum produced when a small household motor is turned on. Interference of this kind

may become very serious, especially in apartment houses in cities where many electrical devices are being operated on the same lines. No general remedy for this condition can be given, since there are so many possible sources and types of interference.

Sometimes two 1 mfd. condensers connected in series with each other and *across* the electric light circuit, are very effective. The junction of the two condensers should be connected to ground. A commercial interference eliminator unit of this type, is shown at the right of Fig. 381. In some cases, it is necessary to connect an r-f choke coil in series with each side of the line, ahead of these condensers The chokes must be wound with wire of sufficient current-carrying capacity to safely carry the full current taken by the receiver. In some power supply units, an r-f choke coil of about 85 millihenries inductance is connected in the positive lead between the filament circuit of the rectifier tube and the first filter condenser to prevent any r-f disturbances from reaching the r-f amplier in the receiver, via the plate circuits. This may be small in size, and wound with wire of small current carrying capacity, since only a small current flows through this circuit.

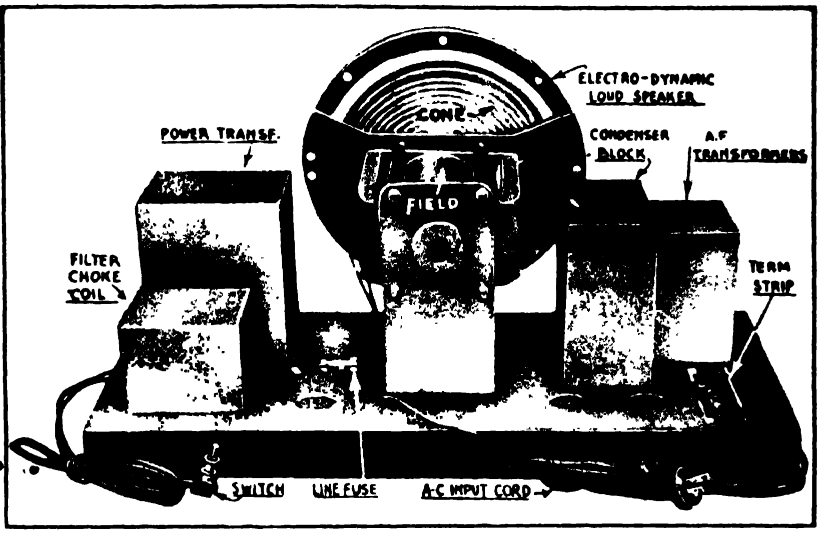
It must be remembered, that all electrical disturbances in electric receivers may not be picked up through the electric light circuit In many cases, the antenna lead-in wire is acted on by the fields created by the disturbances. In such cases, it is necessary to shield the lead-in wire with a copper braid shielding connected to ground. Special shielded, or lead covered wire, is made for this purpose. The entire antenna wire should not be shielded of course, for then it would no longer be acted upon by the fields of the transmitting stations and the signals from the stations would not be received. To test for the source of disturbance, operate the receiver with the noise coming in loudly. Now, disconnect both the antenna and ground wires from the receiver. If the interfering noises stop, it indicates that they were coming in via the antenna circuit. If they continue, they are originating in the power supply line Shielded lead-ins are discussed in Art. 613 and shown in (A) of Fig. 464.

514. Complete "B" power supply unit: Now that we have studied the operation, construction and circuit arrangement of the various parts in an a-c receiver "B" power supply unit, we are prepared to study a typical complete unit of this type. In midget type receivers, the power supply equipment is built on the same chassis with the amplifier and detector portions, since the entire receiver must be built in a single unit, and as compact as possible. This construction may be seen from an inspection of the illustration of the midget receiver chassis in Fig. 286, and that in Fig. 298. In Fig. 298 the shield on the power unit has been removed to show the arrangements of the main parts. U is the power transformer and V is the filter choke. The condenser block is mounted underneath. The rectifier tube is directly in front of the filter choke. The voltage divider resistors are not visible in the illustration.

In the larger receivers which are designed to be installed in console cabinets, the power supply unit, the loud speaker, and the last audio stage, are usually mounted on a chassis separate from that of the amplifier and detector portion. A typical power unit and last audio stage speaker, assembly of this type is shown in Fig. 382. This is sometimes referred to as a "power amplifier". This arrangement results in several advantages. First, when the weight of the power supply unit is included on the receiver chassis, there is a possibility that the receiver cabinet shelf will warp and that the stresses caused by shipping will tend to strain the chassis to an extent which may affect the alignment of the plates in the gang tuning condenser. Another advantage is that the assembly and the later testing and

servicing of the power supply unit are made easy. Also the vibration caused by the loud speaker is not communicated directly to the detector tubes, and therefore less tendency toward howling due to vibration of the tube elements results.

The exact circuit diagrams and arrangements of the types of complete power supply units applied in a-c electric radio receivers, phonograph



Courtesy R C.A Victor Co.

Fig. 382—A typical power supply unit, loud speaker, and last audio stage chassis assembly for an a-c electric receiver The various parts are enclosed in metal protecting cases, and are mounted on a rigid steel base

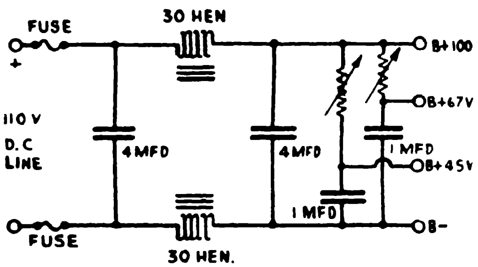
amplifiers and public-address systems, will be studied in the later chapters dealing with these devices.

515. "B" power supply unit for d-c lines: While the voltage appearing across direct current electric light circuits is always in one direction, it is not an absolutely steady, smooth voltage. The reason for this becomes apparent if we refer back to Article 106, and Fig. 68.

It will be remembered, that each d.c. generator used in the power house for generating the direct current voltage, is constructed with a commutator for rectifying the a.c. voltages which are actually generated in the coils of the armature. The resulting voltage is really a rectified a.c. voltage and contains slight ripples or pulsations as shown at (C) of Fig. 68. This condition is similar to that existing in the output circuit of the rectifier tube in the power supply units designed to operate from a.c. lines, only the pulsations are not quite so prominent. If a voltage of this kind is applied to the plates of the amplifier and detector tubes in a radio receiver, every slight change in value of the voltage will cause a corresponding change in the plate current and this being amplified by each tube appears as quite a large ripple in the output current or voltage. The diaphragm of the loud speaker will vibrate in accordance with this ripple in the plate current, and an objectionable low-frequency hum results.

Obviously, in order to make this line voltage suitable for B-supply, the pulsations or "ripples" must be removed. This can be accomplished satis-

factorily by means of a filter system similar to that used in the "B" power supply units already described for a-c circuits, excepting that since the voltage ripples in d-c lighting circuits are not as pronounced as those which appear in the output circuit of a vacuum tube rectifier, a comparitively small amount of filtering is required. Usually a single 30-henry choke connected in series with the line, together with two 2-mfd. filter condensers across the line (one on either side of the choke), are sufficient. In some lines, such as those fed by small d-c electric light systems in rural communities, where the armature on the generator does not contain a great many coils of wire, the ripple in the voltage may be pronounced. In this case two choke coils and larger condensers may be required. These may be



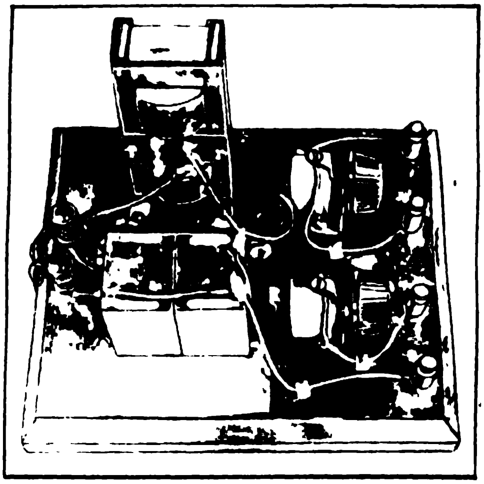


Fig. 383 — Left circuit diagram of a B-power supply unit for operation from the 110 v. d-c electric light circuit. In most cases, only one of the chokes is required, and 2-mf condensers may be used.

Right A unit built from the diagram shown at the left. This is constructed in "bread board" style for laboratory use.

connected as shown at the left of Fig. 383. The output-voltage divider system is of simple form, consisting either of a tapped fixed resistor across the output circuit, or variable resistors as shown. Proper by-pass condensers are shunted across the taps as shown, to prevent interstage coupling due to the common plate circuit impedance in the eliminator. They assist the filtering action of course. If these by-pass condensers are already incorporated in the receiver, they may be eliminated from the power pack. An actual laboratory form of B-power supply unit of this type for d-c circuits is shown at the right. Notice the simplicity of the unit, as compared with the a-c type in which the power transformer, rectifier, etc., are required. The double choke is at the rear, in front of this are the two filter condensers, and at the right are the variable resistors.

One disadvantage of operation from d-c lighting circuits, is that the voltage cannot be stepped up by any simple device such as a transformer, etc., because transformers will not operate on direct circuits. Therefore

the maximum voltage available from the B-power supply unit does not exceed that of the electric light circuit. Actually it is a few volts less, due to the I $\times$ R voltage-drop in the resistance of the filter chokes. The circuit arrangement of a complete receiver designed for operation from the d-c electric light line, will be studied in the next chapter.

516. Measuring the output voltages: When measuring the output voltages delivered by a "B" power supply unit, a high-resistance type voltmeter having a resistance of at least 1000 ohms-per-volt (see Art. 205) should always be employed instead of using an ordinary type of voltmeter. The full-scale range should be adequate for the voltages delivered by the unit.

The ordinary type of voltmeter has a resistance such that the meter draws quite some current from the circuit being measured, for its operation. This amount of current is required to operate the meter. When measuring the voltage of an ordinary low-resistance circuit, this is not objectionable, but when measuring the voltage across a circuit having apparatus of fairly high resistance connected in it, this current drawn by the meter must flow through the resistance of this apparatus, thus causing a "voltage-drop" in each piece of apparatus. Consequently as soon as the meter is connected across the circuit, it causes the voltage existing across the circuit to drop. The voltage reading indicated on the meter is therefore *lower* than that actually existing across the circuit when the meter not connected, so that the *true* voltage reading is not obtained.

The moving-coil element of the high resistance type voltmeter is built so sensitive that it requires only 1 milliampere of current through it to make the needle deflect over full scale (in a 1000 ohms-per-volt meter). Therefore since it draws but a small current from the source, it does not cause the voltage to drop appreciably. Consequently, it gives a reading which is the *true* voltage existing across the circuit. For this reason, a high-resistance type voltmeter should always be used when measuring the output voltage of a "B" power supply unit (see Art. 205).

REVIEW QUESTIONS

1. State three advantages of operation of a radio receiver with a B-power supply unit operating from the a-c electric light circuit, over operation with "B" batteries.
2. Show by diagrams and explain in detail why the voltage from an a-c electric light circuit cannot be used directly for plate voltage supply in a radio receiver.
3. Name the four principle parts of a "B" power supply unit and describe the function of each. Draw a block diagram showing the units connected in proper sequence.
4. Explain the operation of the half-wave rectifier tube.
5. Explain and show by diagrams, how two half-wave rectifier tubes may be connected to form a full-wave rectifier circuit.
6. Explain the operation of the full-wave rectifier tube.
7. What advantages does the mercury vapor rectifier tube possess over the vacuum type? What feature of its construction is responsible for this?
8. Draw a circuit diagram of a complete "B" power supply unit for operation from the a-c line. A full-wave rectifier tube is employed, and the filter contains a 30 henry choke and the field

of an electro-dynamic loud speaker. The unit is to supply 300, 180 and 45 volts to the plate circuits of the tubes in the receiver. Explain the operation of each part in the unit.

9. Draw the circuit diagram for four filter system arrangements. Explain the operation and advantages of each.
10. What are the requirements of (a) a satisfactory choke coil; (b) a satisfactory filter condenser, in a filter system.
11. Which condenser in a two-section filter is called upon to withstand the highest voltage? Why?
12. Draw the circuit diagram of a "B" power supply unit arranged to provide the "C" bias voltage for the push-pull tubes in the last audio amplifier stage of the receiver.
13. It is desired to obtain a plate voltage of 135 volts for an amplifier tube whose plate current is 5 milliamperes. A voltage source of 300 volts is available. Show by a diagram, how this may be arranged, and calculate the values of the parts required.
14. The potential of the high-voltage line in a radio receiver is 300 volts. It is desired to operate four '27 type amplifier tubes, and two '47 type pentode tubes in push pull, at their maximum rated plate voltages, from this line. Draw the circuit diagram showing all connections, and calculate the values of all resistors required to supply proper plate and grid voltages for the tubes. (See Fig. 214.)
15. Why should a "high-resistance" voltmeter be used for all voltage measurements in "B" power supply units?
16. Draw the circuit diagram for a "B" power supply unit designed to operate from the 110-volt d-c electric light circuit. The voltage divider is to be of the fixed-resistor type and is to be designed to supply 15 m.a. at 90 volts, 5 m.a. at 45 volts, and 5 m.a. at 22½ volts. The maximum output voltage available is 100 volts.
17. Why is it necessary to use a filter in a unit of this kind? Is more, or less, filtering required than in the case of a power supply unit operating from an a-c line? How does this affect the size of the chokes and condensers, and their cost?
18. What will happen in a "B" power supply unit operating from an a-c line, if the paper dielectric in one of the filter condensers becomes punctured? How does this affect the operation of the receiver? What would happen if electrolytic type filter condensers were used?
19. What will happen if the windings in one of the filter chokes becomes; (a) short-circuited; (b) open-circuited?
20. What happens if an open-circuit occurs in one of the voltage divider resistances, if the system shown in Fig. 375 is used?
21. Explain what happens when the rectifier tube gets old and its electron emission diminishes greatly.

CHAPTER 28

ELECTRIC RECEIVERS

ELECTRIC RECEIVERS — D-C ELECTRIC RECEIVERS — SERIES FILAMENT CIRCUIT — TYPICAL D-C ELECTRIC RECEIVER — A-C TUBE ELECTRIC RECEIVERS — TYPICAL T-R-F A-C ELECTRIC RECEIVER — TYPICAL SUPERHETERODYNE A-C ELECTRIC RECEIVER — TYPICAL MIDGET SUPERHETERODYNE RECEIVERS — GENERAL CONSIDERATION OF A-C RECEIVER DESIGN — HUM IN ELECTRIC RECEIVERS — REVIEW QUESTIONS.

517. Electric receivers: In Chapter 27, various types of practical "B". power supply units, for supplying unvarying, smooth, direct current voltages to the plate circuits of radio receiving equipment were described. These take their power from the electric light socket, one form being used with a-c lighting circuits and another form being used with d-c lighting circuits. The problem of supplying the current for heating the filaments of the tubes in the receiver, is solved by using tubes of the indirect-heater type, in which the electron-emitting cathode is heated by a heater-filament electrically insulated from it.

Before proceeding further with the study of electric receivers, it will be well to become familiar with the nomenclature which has originated in connection with this subject. It is obvious that various combinations of electrical operation methods can be resorted to in any set. Thus a receiver may use a "B" power supply unit operated from the electric light line, but use a storage "A" battery for filament supply. Such a set is not a true electrically-operated receiver.

The following standard definitions adopted by the Radio Manufacturers Association will be used in this book.

(1) *"Battery-Operated Receiver"*: A radio receiver designed to operate from primary batteries and (or) storage batteries.

(2) *"Electric Receiver"*: A radio receiver operating from the electric light line without using batteries.

(3) *"A-C Tube Electric Receiver"*: A radio receiver employing tubes which obtain their filament or heater currents from an a.c. electric light line without the use of rectifying devices, and with a built-in rectifier for the plate and grid-biasing potentials.

(4) *"D-C Tube Electric Receiver"*: A radio receiver employing tubes which obtain their filament or heater current from a direct current electric light line, without the use of rectifying devices, and with a built-in power supply for the plate and grid biasing potentials.

It is evident from these definitions that a true electric receiver does not use batteries of any kind, all filament, plate, and grid voltages being obtained entirely from the power taken from the electric light circuit. Since there are two forms of current, (a-c and d-c), furnished by electric light circuits, the two types of electric receivers defined in (3) and (4) will now be studied.

518. D-C electric receivers: In many localities, *direct current* is furnished by the electric light and power company, for electric lighting. The electric radio receivers to be used in these places, must be designed to operate with this direct current as a source of power. As outlined in Article 515, the voltage and current in a commercial d-c electric light

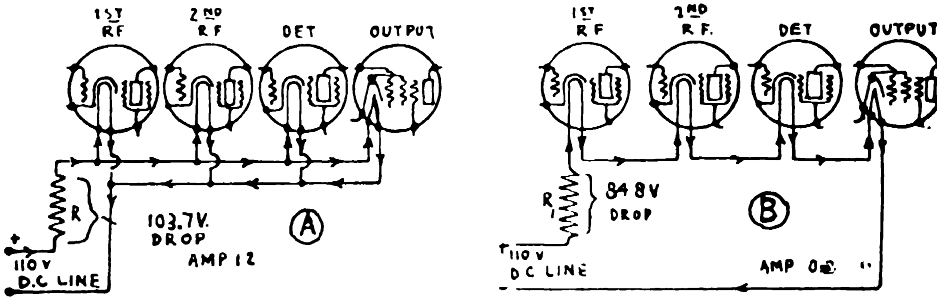


Fig 384--(A) All of the tube filaments connected in parall
(B) All of the filaments connected in series in a d-c electric receiver

circuit is not absolutely smooth and unvarying, but contains pulsations or "ripples" due to the action of the commutator on the d-c generator. A satisfactory filter system for smoothing the voltage and current for the plate circuits of the tubes in the receiver was described in Article 515. This solves the problem of d-c electric operation insofar as the plate circuits are concerned. It is not practical to filter the filament-heating current for the tubes, because the cost of such a filter would be unreasonably great. It is really not necessary to filter this current anyway. If tubes such as the '12A type, or the later '36, '37 and '38 types, are employed in the receiver, no objectionable hum results if the unfiltered current from the line is used for heating the filaments. While good d-c electric receivers have been constructed using '12A type tubes, the development of the separate-heater type tubes referred to above, makes possible the construction of d-c electric receivers whose operating characteristics are very much superior. We will consider the use of these separate-heater type tubes only.

519. Series-filament circuit: Since the filaments of the d-c electric receiver are to be operated from the 110 volt electric light circuit, two filament circuit arrangements are possible. These are, the parallel

arrangement, and the series arrangement. If we consider the use of separate-heater type tubes such as the '36, '37 and '38 which were developed especially for service of this kind, we find from Fig. 214, that they require a filament voltage of 6.3 volts and take a filament current of 0.3 ampere each.

Let us consider the simple four-tube d-c electric receiver, whose circuit is shown in Fig. 385, and in which these types of tubes are employed. If the filaments of the tubes were connected in parallel, as shown at (A) of Fig. 384, a resistor R would have to be connected in series with them to drop the line voltage of 110 volts, to 6.3 volts for the filaments. The total filament current, $0.3 \times 4 = 1.2$ amperes would flow through this resistor. The voltage drop required in it, would be $110 - 6.3 = 103.7$ volts. Therefore its resistance would have to be equal to $R = E/I = 103.7/1.2 = 86.4$ ohms. The power dissipated in the resistor would be equal to $W = I^2R = 1.2 \times 1.2 \times 86.4 = 124.4$ watts. This is quite a large amount of electrical power to be dissipating in the resistor in the form of useless heat, just to drop the voltage down to the proper value. The total power taken from the line for the entire filament circuit will be, $W = E \times I = 110 \times 1.2 = 132$ watts. Let us see what happens if we connect the filaments in series, as shown at (B). The total current in the circuit is now equal to 0.3 ampere—the same as that for one tube. The total voltage to be applied to all of the filaments in series is $6.3 \times 4 = 25.2$ volts. Therefore a series resistor R_1 must be connected in the circuit as shown, to drop the voltage to the proper value. The voltage drop in R_1 must be equal to $110 - 25.2 = 84.8$ volts. The resistance required to produce this voltage drop is equal to $R = E/I = 84.8 \div 0.3 = 282$ ohms. The power dissipated in this resistance will then be equal to, $W = I^2R = 0.3 \times 0.3 \times 282 = 25.4$ watts. The total power taken from the line for the entire filament circuit is $W = E \times I = 110 \times 0.3 = 33$ watts.

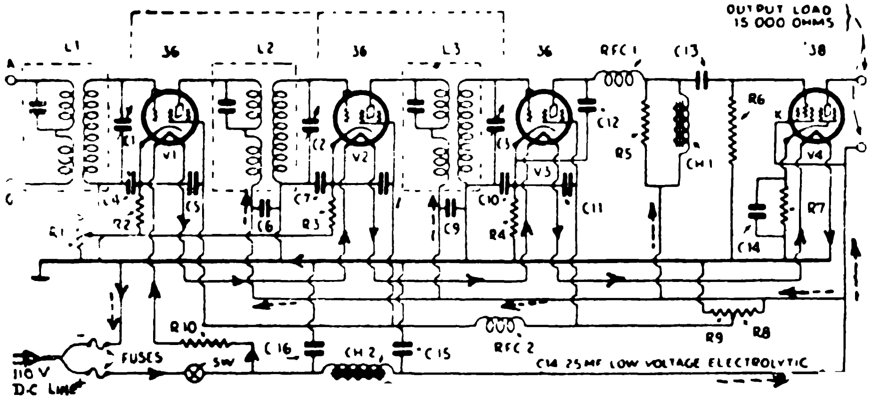
The advantage of the series-filament connection for receivers of this type is evident. In the first place, since the voltage-dropping resistor must dissipate less power in the form of heat in the series arrangement, it can be constructed smaller and more cheaply. In the second place, a large saving in the power taken from the electric light circuit results. In this case, it is 132 watts for the parallel arrangement, and only 33 watts, (¼ as much) for the series arrangement. A large amount of the power is wasted in the series resistor in the parallel arrangement. The advantages of the series arrangement are apparent. Insofar as the heating of the filaments is concerned, one circuit is just as effective as the other.

520. Typical d-c electric receiver: The complete circuit diagram of a 110 volt d-c electric receiver employing the series-filament connection, is shown in Fig. 385. Four separate-heater tubes are employed. Due to the separate-heater construction, the filament current need not be filtered, since the ripples in it do not affect the emission of electrons from the cathode. The filament current flows from the positive side of the 110 volt d-c lighting circuit through the "on-off" switch, up through the 282 ohm resistor R_{10}, through filaments V_1, V_2, V_3 and V_4, and back to the negative side of the line, as shown by the solid arrows.

An ordinary 40 watt, 110 volt incandescent lamp bulb could be used as resistance R_{10}, since it has a resistance of approximately 300 ohms and would allow about 0.29 amperes to flow through the filament circuit when the line voltage was 110 volts. The tubes would operate satisfactorily with this current, and some margin of safety would be secured in the event of the line voltage rising to 115 volts or more at times.

The receiver employs two stages of tuned r-f amplification using screen grid tubes, a screen grid power detector, and a power pentode output tube. The r-f coils L_1, L_2 and L_3, are of the special resonated primary type, (see (3) of Fig. 290A), for

uniform r-f amplification. Tuning condensers C_1, C_2 and C_3 are the sections of a 3-gang condenser, for singe-dial tuning control. The grid-bias voltages for the tubes are obtained by means of the voltage drops in the resistors R_2, R_3, R_4 and R_7 respectively, connected in the cathode circuits. By-pass condensers of suitable values shunt these resistors. The volume control resistor R_1 in the common cathode return circuit, varies the grid bias on the two r-f tubes. The filter system for the plate voltage supply consists of 30 henry choke CH_2 connected in series with the positive side of the line, and filter condensers C_{15} and C_{16} connected across the line. The paths of the plate currents of the various tubes, are shown by the dotted arrows. The proper screen grid voltage is obtained from potentiometer R_8 connected from B— to the B+ line. The r-f choke RFC_2 and by-pass condensers C_5 and C_{11} in the screen grid circuits prevent interstage coupling which might otherwise be caused by the



L_1=Shielded Antenna Coil
L_2, L_3=Shielded R.F. Coils
R.F.C.$_1$—R.F.C.$_2$=85 M.H. R-F Chokes
CH_1=A-F Transformer Secondary
CH_2=30 Henry Choke
R_2, R_3=800 Ohms
R_1=50,000 Ohm Volume Control
R_4=10,000 Ohms Bias Res
R_5, R_6=.5 Meg.
R_9=5000 Ohms

C_1, C_2, C_3=3 Gang Variable Cond.
C_4, C_5, C_6, C_7, C_8, C_9, C_{13} .01-μF. By-pass Cond.
C_{10}, C_{11}=1μF By-pass Cond.
C_{12}=.001 μF By-pass Cond.
C_{14}=25 μF Low-voltage, Dry-electrolytic Cond
C_{15}, C_{16}=200 v. Filter Cond. (One 2μF, One 4μF)
R_7=1200 Ohm Bias Res.

Courtesy Radio Craft Magazine

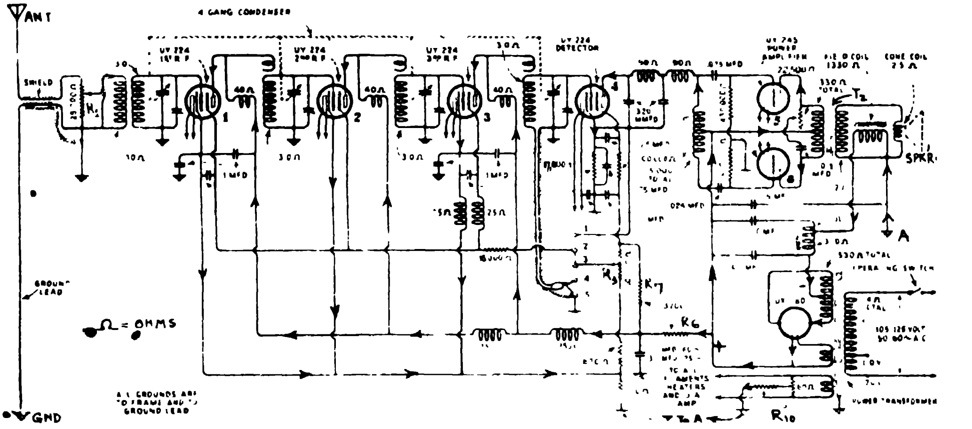
Fig 385—A typical modern 4-tube receiver designed to operate from the 110-volt d-c electric light line It employs two screen grid t-r-f amplifier stages, a screen grid detector, and a power pentode output tube—all being of the separate-heater type

common impedance in the circuit. Since grid-bias resistor R_7 has a resistance of only 1200 ohms, a rather large value of by-pass capacity C_{14} must be connected across it to prevent serious degenerative effects in the pentode circuit due to the varying plate current flowing through R_7. A low-voltage type electrolytic condenser is suitable for this.

It should be remembered that the line plug for any d-c electric receiver must be inserted properly in the receptacle so that the "positive" side of the line connects to the "plate" side of the circuit. If the plug is reversed, the plates of the tubes have a negative potential applied to them, and the receiver will not function.

521. A-C tube electric receivers: The construction of a-c electric receivers embodies the many principles which we have studied in previous

chapters. In general, there are three main circuit arrangements employed in receivers of this type. The first, is the ordinary t-r-f receiver which employs several stages of tuned radio-frequency amplification. The second is the band-pass selector type receiver, in which the tuning is accomplished in a band-pass selector preceeding the amplifier tubes, as shown in Fig. 258. Then the wanted signal is amplified by several stages of untuned r-f amplification. The third is the superheterodyne circuit. Of course, each of these employs a detector and at least one audio stage. The r-f amplifiers of modern receivers employ screen-grid type tubes on account of their many advantages. The detector tubes may either be of



Courtesy R C A Victor Co

Fig 386—Typical a-c electric screen grid t-r-f receiver employing 3 stages of t-r-f amplification, screen grid detector, and single stage push-pull a-f amplifier The arrows show the directions of flow of the plate currents of the various tubes

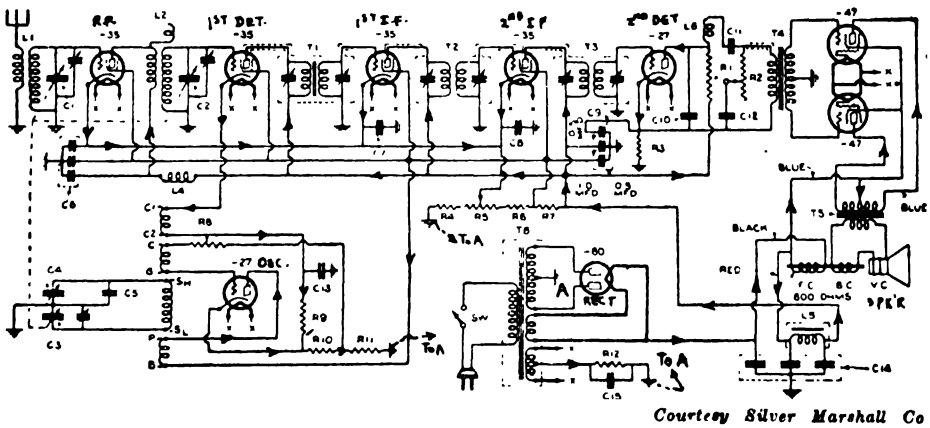
the screen-grid, the 3-electrode, or the power pentode types. All a-c electric receivers contain a rectifier, filter, and voltage divider system for making the a-c line voltage suitable for use in the plate circuits of the tubes. Separate-heater type tubes, heated by raw a-c current obtained from low-voltage windings on the power transformer, are commonly employed, with the exception of the power amplifier tubes, which are usually of the direct-heater, thick-filament type. Grid-bias voltages are obtained by utilizing the voltage drops occurring in resistors of proper values connected properly in the circuit for this purpose.

522. Typical t-r-f a-c tube electric receiver: The circuit diagram of a typical t-r-f a-c electric receiver is shown in Fig. 386. This employs three stages of tuned screen-grid r-f amplification, a screen-grid power detector, and a single push-pull audio stage using '45 type power amplifier tubes. An analysis of this circuit follows:

The four tuning condensers are constructed in gang form for single-dial tuning control. The r-f coils have a "capacity winding" shown at the top, to equalize the r-f amplification over the broadcast band (see (2) of Fig. 290A). A dual-type volume control consisting of potentiometer R_1 in the antenna circuit and R_3 in the screen

grid circuits of the r-f tubes is employed. Tone control is obtained by means of the 22,500 ohm resistor and 0.1 mf. condenser, across the primary of the push-pull output transformer. All of the filaments of the tubes are connected in parallel across the 2.5 volt heater winding on the power transformer. A full-wave rectifier tube is employed and the rectifier filter system is of the Miessner type, with a tapped filter choke in the negative side of the circuit. The field of the loud speaker connected in series with this, also acts as a filter choke. The proper plate voltage for the r-f tubes is obtained by means of the voltage-dropping resistor R_6. The direction of the plate current flow of each tube is shown by the arrows. Resistor R_7 drops the voltage to the proper value for the screen grids. The grid bias voltage for the power amplifier tubes is obtained by the voltage drop across resistor R_{10} connected in the plate current return circuit of these tubes. The resistance of the plate circuits of the power amplifier tubes in push-pull is matched to the low impedance of the speaker voice-coil by means of the special output transformer T_2.

523. Typical superheterodyne a-c tube electric receiver: The complete circuit diagram of a typical superheterodyne a-c electric receiver is shown in Fig. 387. This employs a stage of t-r-f amplification ahead of the first detector, using a variable-mu type tube. Two stages of intermediate-frequency amplification are employed, with band-pass tuner interstage coupling transformers T_1, T_2 and T_3, each having a tuned primary and a tuned secondary. The second detector is of the 3-electrode power type, and feeds into a push-pull power pentode amplifier stage. The pair of '47 type pentode tubes in push-pull are capable of handling from



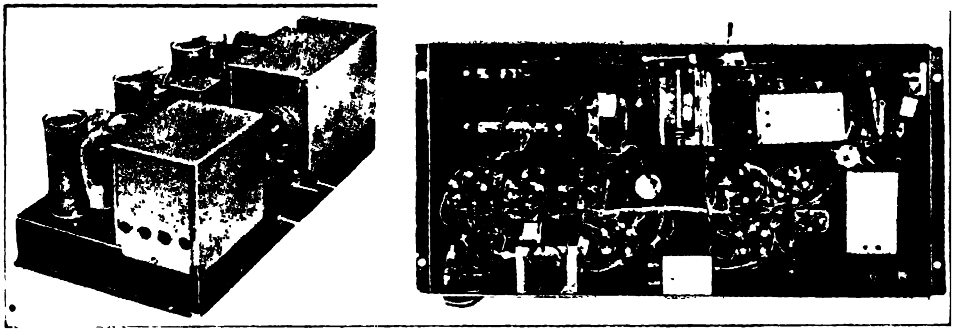
Courtesy Silver Marshall Co

Fig. 387—Circuit diagram of a typical a-c tube electric superheterodyne receiver employing variable-mu and power pentode tubes. The arrows show the paths of the plate currents. The actual receiver is shown in Fig. 388

6 to 7½ watts of power—which is ample for home requirements. Excellent volume control is obtained by means of resistors R_4 and R_5, which vary the grid bias applied to the variable-mu amplifier tubes. Due to the fact that these tubes can handle large values of signal voltage without rectification, cross modulation effects are not troublesome, and no preselector is required ahead of the first r-f tube. The oscillator tuning cir-

cuit is of the "padded" type designed to be tuned in synchronism with the r-f and detector tuning circuits.

The plate current of the second detector tube is brought through resistor R_1 and is isolated from the primary of the audio transformer T_4 by condenser C_{11}, the combination of R_1, C_{11}, and the primary of T_4 making up the Clough system of tuned a-f amplification. This is designed to produce slight over-amplification of the audio fre-



Courtesy Silver Marshall Co.

Fig 388—Top and bottom views of the a-c superheterodyne receiver shown in Fig. 387. Note the sturdy metal chassis, and the simplified wiring which results from a careful design and proper layout of all parts and wiring.

quencies between 50 and 100 cycles, to compensate for the deficiencies of the loud speaker on these frequencies (see Arts 431, 451 and 485). The tone control circuit consists of rheostat R_2 of 500,000 ohms resistance, and condenser C_{12} of .025 mf. capacity.

The power supply unit utilizes a full-wave rectifier tube, with power transformer T_6 supplying all filament and plate voltages. Winding X-X supplies the low voltage a-c current for the parallel-connected filaments of the tubes in the receiver. Resistor R_{12} is the C-bias resistor for the power pentode tubes. The filter circuit utilizes one choke coil L_5, and the 800-ohm speaker field F.C., together with three 4-mf. dry electrolytic condensers C_{14}, and in addition, the filtration effect provided by the hum-bucking coil B.C. in the speaker voice-coil circuit and the additional by-pass condensers in the plate circuits. The plate voltage for the power pentodes is taken off from the point between the two chokes. The voltage divider consists of resistors R_7, R_6, R_5 and R_4 connected between the high voltage side and B—. The high voltage is supplied direct to the plates of the amplifier and detector tubes. The paths of the plate currents through the receiver are shown by arrows on the diagram. It will be very instructive for the reader to trace these paths through the receiver. Resistor R_7 drops the voltage to the proper value for the screen grids and the plate of the oscillator tube. Resistor R_4 and the portion of R_5 included between this end and the movable arm determine the control-grid bias voltage of the r-f and i-f tubes, this being employed as the volume control. Resistor R_4 is used to assure that at least a certain value of grid-bias potential will be applied to the amplifier tubes even when the arm of the volume control resistor R_5 is set at its extreme left position.

The loud speaker is designed especially for over-accentuation of the high audio frequency note reproduction, to compensate for the suppression of the upper side band frequencies in the r-f and i-f amplifiers in an attempt to secure exceedingly sharp tuning in these circuits. The proper combination of low-frequency compensation in the audio amplifier, and high-frequency compensation in the loud speaker, (see Article 485), gives an overall frequency-response which provides satisfactory reproduction,

considering that the 10 kc channel basis, on which stations are allowed to transmit, permit them to transmit only those audio frequencies up to about 5,000 cycles. The tone control provides an adjustment of the high-frequency response to suit the taste of the individual listener.

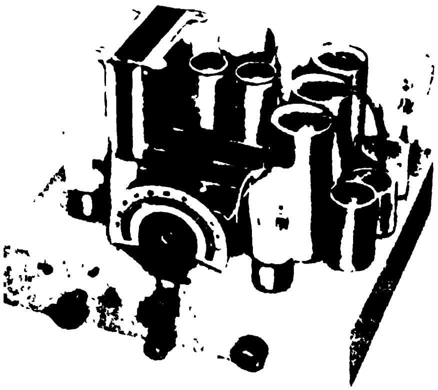
The sensitivity of this receiver is such, that an actual signal voltage of 2.84 to 1.85 microvolts (depending on the frequency of the station) applied in the antenna circuit (standard 4 meter effective height) will produce the standard output of 50 milliwatts in the output circuit. These figures divided by 4, give a sensitivity of from .71 to about .46 microvolts-per-meter (see. Art. 347). Sensitivities of this order are really higher than can be utilized in practice in most locations because of static, electrical disturbances, etc., and are high enough to receive any signal sufficiently above the prevailing noise level, to be intelligible.

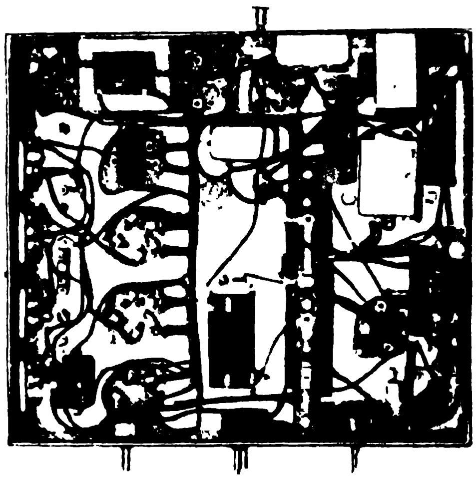
A top view of this receiver showing the simplified construction, is shown at the left of Fig. 388. The power supply unit is contained in the ventilated shield at the front left. The gang tuning condenser and oscillator tube are at the right. At the rear are the various tubes, shielded from each other. The rectifier and power amplifier tubes are shown at the lower left. The illustration at the right shows the arrangement of the wiring and the smaller parts such as tube sockets, audio transformers, plate and C-bias resistors, by-pass condensers, volume and tone control resistors, etc., under the chassis. Notice that while the circuit diagram of Fig. 387 looks fairly complicated, the actual construction and wiring of the receiver itself is also simple, as a result of the great care observed in laying out the parts and wiring.

524. Typical midget superheterodyne receivers: The so-called *midget type* receivers, have attained a definite status in the low-price radio receiver field. They are constructed in very compact form, and are enclosed, together with the electro-dynamic loud speaker, in very compact cabinets which may be placed on a suitable table, and readily be transported. While it is true that midget type receivers are not able to reproduce the lower audio frequencies down to anywhere near 40 cycles, due to the fact that the loud speaker baffle which is formed by the receiver cabinet is necessarily very small, fairly pleasing reproduction is obtained by properly suppressing the high-note reproduction so the tone appears low to the ear. Of course this is not true undistorted reproduction. From the standpoint of amplification, the midget type receiver may be constructed to have practically as high a value of sensitivity as the larger receivers, provided a reasonable amount of cabinet space is available for the parts. The results accomplished by receiver designers in this field, are little short of marvelous. Of course, the development of the high-amplification screen-grid and variable-mu tubes, the high power sensitivity pentode tubes, the development of the compact form of dry electrolytic filter condensers, and the compact form of electro-dynamic loud speaker have all assisted materially in making this form of receiver possible. A typical midget receiver chassis and loudspeaker is shown in Fig. 286. An idea of the relative size and spacing of the parts may be obtained, when it is realized that this entire chassis is just 12 inches wide. A sensitivity of 6 to 10 microvolts-per-meter is obtained. Another midget superhetero-

dyne receiver whose chassis measures only 12 inches long, 10¾ inches deep and 8 inches high overall, is shown in Fig. 389. Notice the compact arrangement of the parts and the simplified wiring under the chassis.

Both the t-r-f and the superheterodyne circuits have been used extensively in receivers of this type. Of course, screen-grid type tubes, and power-pentode output tubes (either singly or in push-pull), are employed almost exclusively, since less stages of amplification are required when they are employed. The circuit diagram of a typical t-r-f midget receiver is shown in Fig. 390. This contains two stages of tuned radio-frequency amplification employing variable-mu tubes, a screen grid power detector





Courtesy Radio News Magazine

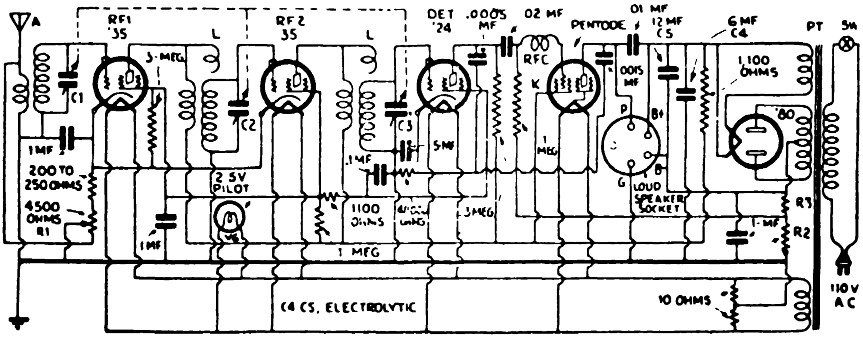
Fig 389—Top and bottom views of a typical midget superheterodyne chassis which measures only 12x10¾ inches This contains two stages of i-f amplification, first and second detectors, and a push-pull audio output stage—8 tubes in all, including the rectifier.

and a single power-pentode output tube. The r-f transformers employ the small capacity coupling winding to equalize the sensitivity throughout the tuning range. The power detector is resistance-capacity coupled to the output '47 type pentode tube. The full-wave rectifier circuit employs two electrolytic filter condensers, and the field coil of the loud speaker, (which connects between G and B in the loud speaker plug socket shown) acts as a filter choke in the B— lead. The reader should trace and study the various features of circuits such as these, as much valuable practice and knowledge will thereby be obtained.

Fig. 391 shows the rear view of a typical midget receiver chassis with electro-dynamic loud speaker, in a small midget cabinet. Notice the loud speaker, mounted against the top of the front face of the cabinet. The chassis is suspended in the floating rubber suspensions shown at the sides

of the cabinet, to reduce the vibration which would otherwise be communicated directly from the loud speaker to the tubes, by the cabinet.

525. General consideration of a-c receiver design: It is obviously impossible because of space limitations, to present and discuss in a text of this kind, a large number of circuit diagrams of commercial receivers being manufactured. The author does not feel that it would be desirable to include these anyway, for the details of vacuum tube and radio receiver designs are constantly being improved and changed from



Courtesy Crosley Radio Corp.

Fig. 390—Circuit diagram of an a-c electric midget type receiver employing two stages of screen-grid t-r-f amplification, power detector, and a single power pentode audio output tube

season to season. It is felt that the typical circuits presented here will enable the reader to understand the general circuit arrangements employed in the various types of receivers. It will be found, that as a rule, receivers marketed by various manufacturers differ only in minor circuit details, structural design of the parts and mechanical arrangement. The student who is well grounded in the fundamentals concerning vacuum tubes and the theory of receiving systems should have no difficulty in analyzing the circuit of any particular receiver in which he may be interested, at any time. In fact, it is strongly urged that he develop the habit of studying and analyzing the latest receiving circuits which are published in the popular radio magazines and circuit diagram manuals. A little experience in doing this, will enable him to quickly analyze the important features of any receiver circuit in but a few minutes.

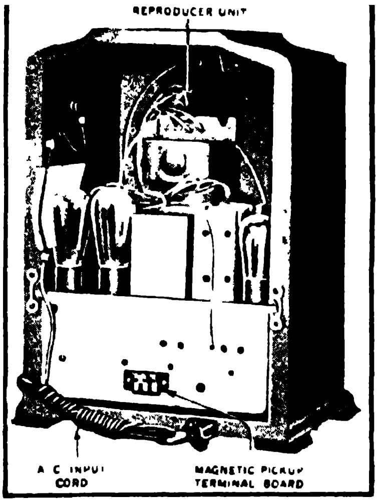
Receiver design has progressed so rapidly in the United States that it is difficult to see where any radical improvement in operating characteristics can be made—under present broadcasting conditions. Medium priced receivers are available, which have as much sensitivity as it is possible to employ in practice on account of the "noise level" resulting from all sorts of extraneous electrical disturbances such as "static", disturbances set up by electrical machinery and appliances, etc. Tone quality in many of the larger receivers employing satisfactory baffling for the

loud speaker, has been improved to a point where the average listener would not notice any further improvement. It would seem that any further radical improvements which may be effected will be along the lines of even further simplification and reduction of size and cost of the receiver, rather than in marked improvements in operating characteristics.

525A. Hum and noises in electric receivers: An electric receiver should operate without objectionable hum or other extraneous noises due to the electric operation. Absolutely silent operation is difficult to obtain in receivers which reproduce the audio frequencies down to 60 cycles. However, in well designed receivers, the hum is reduced to a value where it does not cause objectionable disturbance, and is practically unnoticeable.

One frequent cause of a-c hum in a receiver, is the interaction between the magnetic fields of the parts in the power supply unit and those in the audio amplifier. As shown in Fig. 391A, the power transformer used in the power unit, as well as the filter chokes. and the audio transformers used in the receiver, have magnetic fields which spread out to a considerable distance in their vicinity. If these parts are placed close to each other so that the fields and windings interact, alternating voltages will be induced in the chokes and the audio-frequency amplifier transformer coils, and will be amplified along with the signals, producing a bad hum in the loudspeaker. Any slight a-f voltage induced in the first audio transformer is especially liable to cause troublesome hum, as this voltage is amplified several hundred-fold by the audio amplifier. The use of a resistance coupled first audio stage eliminates this, since a resistance coupling unit does not have coils to pick up induction effects. The use of a resistance-coupled audio stage following the detector in a-c tube electric receivers has become very popular for these reasons.

The power transformer, the chokes, and the audio transformers (especially the first stage one) must be kept a suitable distance apart to avoid this trouble. Thus distance is best determined by experiment with the particular units used, by shifting the parts around. This trouble can also be reduced effectively by locating the parts in such relation to each other that the magnetic fields are at right angles to each other. Also keep all grid and plate leads as short as possible, and away from all circuits carrying alternating current. The wires carrying a-c should be twisted to prevent magnetic induction effects (see Art. 124). Faulty a-c tubes or faulty rectifier tubes are also a frequent cause of hum in a set. They can be detected by plugging new tubes in their places while the receiver is operating.



Courtesy R.C.A. Victor Co.

Fig 391—Rear view showing position of chassis and loud speaker in a typical midget type receiver. Notice the compact construction.

Noisy sets usually present quite a problem, as it is usually difficult to locate the source of the troubl . To locate the cause of noises, first find out if the scratchy noises are coming from the aerial circuit or from the set, tubes, power unit, or batteries. To do this, first operate the set so the scratchy noises come in loudly. Now disconnect both the aerial and ground from the set and short the "Ant" and "gnd" terminals of the receiver with a short piece of wire. If the noises stop, it indicates that they have been caused by some outside electrical disturbance sending the electrical impulses to the aerial. In this case, you will have to try to locate the cause of the trouble and eliminate it.

If the noises continue when the aerial is disconnected, it indicates that they originate in the equipment. Check over every connection to make sure it is made tightly. Now try a new tube in each socket at a time to find out if one of the regular tubes is causing the noises.

Hum or howling is sometimes caused by one or more microphonic tubes in the set. To locate a microphonic tube, operate the set so that the hum or howl comes in very loud. Now press your hand firmly down on each one of the tubes in the set in turn. When you do this to the microphonic tube, the hum will decrease in strength or disappear altogether. It should either be replaced with a new tube, or one of the weighted "howl-arresters" made for this purpose should be placed on it. They can

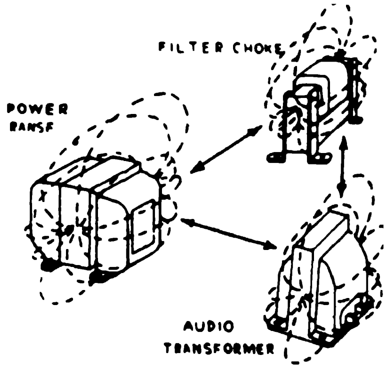


Fig 391A—How the external or "stray" varying magnetic fields existing in the space around the power transformer and filter choke coils in a power supply unit may act on the windings of an audio transformer and induce 60 or 120-cycle a-c voltages in these windings These induced hum-voltages will be amplified greatly by the a-f amplifier in the receiver and will result in an objectionable 60 or 120-cycle hum from the loud speaker To prevent this, the a-f transformer should be mounted at some distance away, and with its core at right angles with those of the other units

be purchased at radio stores for a nominal sum. Placing the speaker too close to the set sometimes causes a hum or howl due to the strong sound waves from the speaker setting up a mechanical vibration of the tubes. When the tube elements vibrate (at the audio frequency), the distance between them changes, resulting in corresponding audio-frequency plate current changes which are amplified by the audio amplifier, resulting in a hum or a bad howl. The remedy for this is to mount the speaker at some distance from the set, or use weighted rubber "howl-arresters" on the sensitive tubes located by the above tests.

REVIEW QUESTIONS

1. Show by an actual example, why it is more satisfactory and economical to operate the filaments of the tubes in a d-c electric receiver in series, than in parallel.
2. A d-c electric receiver is to be constructed with six tubes having their filaments connected in series across a 110 volt line. Each filament is rated at 5 volts and 0.25 ampere. What must be the resistance value and wattage rating of the resistor which must be connected in series with the filament circuit? Draw a diagram showing the complete filament circuit only.
3. Describe briefly what must be done to the current from the d-c electric light line before it can be applied in the plate circuits of the receiver.
4. Draw a diagram showing the "B" supply circuits and filter for the receiver in question 2.
5. Explain why it is not possible to use "raw" a-c applied directly to the plate and grid circuits of an a-c electric receiver.
6. Draw a circuit diagram showing the "B" and "C" circuits of an ordinary 5 tube t-r-f a-c electric receiver, complete with the "B"

power supply unit in which the speaker field and an additional 30 henry choke coil are used in the filter.

7. What is the advantage of using screen-grid tubes of the variable-mu type instead of the 3-electrode type, in the r-f or i-f amplifier circuits of a receiver?
8. What are the advantages of using power pentode tubes instead of 3-electrode power tubes in the output stage?
9. What are the relative advantages of a-c and d-c current supply for the operation of electric receivers?
10. Draw the complete circuit diagram, with all filament, plate, and grid-bias voltage supply circuits, of a three-stage tuned r-f a-c electric r-f amplifier, using variable-mu type tubes. Use your own ideas regarding volume control, etc.
11. Add a screen-grid power detector to the circuit in the previous question.
12. Add a push-pull audio output stage using pentode tubes, to this diagram. Draw the loud speaker connections and a tone control in the circuit, using your own ideas, as to their proper arrangement. Now explain the main features of the entire circuit.
13. Repeat questions 10, 11, 12 for a superheterodyne type receiver.
14. Explain why separate-heater type tubes are used in a-c electric receivers.
15. What improvements in radio reception would result, if each broadcasting station were allowed to transmit a band of frequencies 20 kc wide instead of the 10 kc band now employed? What changes in present receiver design would be necessary to enable the benefits resulting from such a change to be realized at the receiving end?
16. Describe the construction of a 3-electrode separate-heater type amplifier tube, and explain how filament operation with a-c current is possible without resulting in objectionable hum.
17. Explain two advantages of using resistance coupling between the detector and first audio stage in an a-c tube electric receiver using a power detector.
18. Explain in detail how you would proceed to determine whether "scratchy", "crashing" noises issuing from the loud speaker of an electrically-operated radio receiver are due to electrical disturbances reaching the set by way of the antenna-ground circuit, or reaching it by way of the electric light supply line.
19. If your test in question 18 indicates that the disturbances are reaching the set via the antenna-ground circuit, and further tests show them to be induced in the antenna lead-in wire only, how could you eliminate them? Explain!
20. If the disturbances are reaching the set via the electric light supply line, how would you prevent them from reaching the set? Explain, with diagram!

CHAPTER 29

AUTOMOBILE AND AIRCRAFT RECEIVERS

RADIO RECEIVERS IN AUTOMOBILES — SELECTION OF THE TUBES — THE RECEIVER — THE LOUD SPEAKER — THE "B" BATTERIES — TUNING CONTROL — THE ANTENNA AND GROUND SYSTEM — IGNITION SYSTEM INTERFERENCE — AIRCRAFT RADIO RECEIVER REQUIREMENTS — ENGINE IGNITION INTERFERENCE — SHIELDING THE IGNITION SYSTEM — THE ANTENNA SYSTEM — RADIO EQUIPMENT — RADIO BEACONS — REVIEW QUESTIONS.

526. Radio receivers in automobiles: The use of radio receivers installed in automobiles, either for entertainment purposes, or for general police signal work, etc., presents some special design and installation problems which are not encountered with home receivers. These problems arise from the special operating conditions which exist in automobiles.

The most important of these special operating conditions is the fact that the auomobile radio receiver must obtain all filament, plate and C-bias voltages for the operation of its tubes either directly (or indirectly) from the same storage battery (usually 6 or 12 volts) which is used for the starting, lighting and ignition system of the automobile. Therefore, it should not require large filament or plate currents, for this would impose an excessive current drain on the car battery. A heavy current drain is especially objectionable in cold weather, when it is necessary to maintain the storage battery in fully-charged condition at all times in order to facilitate the operation of the self-starter motor when the engine is cold and the lubricating oil is stiff.

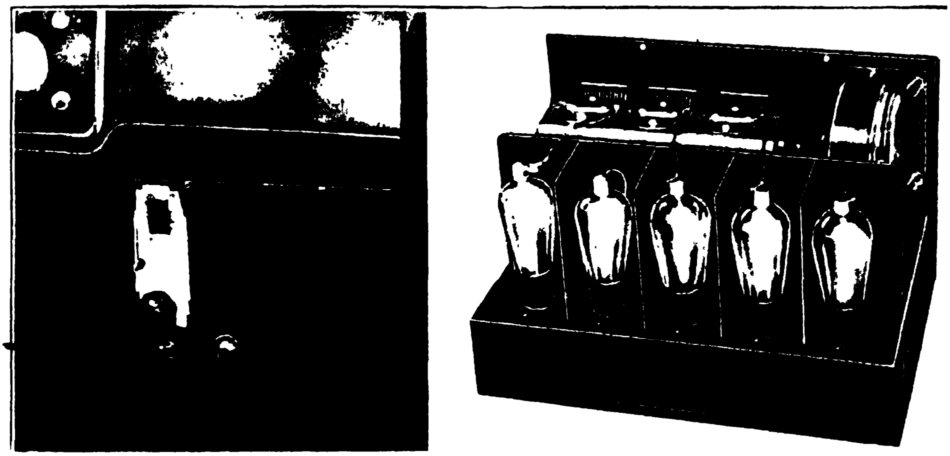
The "filament" current for automobile radio receivers is usually obtained directly from the car storage battery. The "plate" and "C-bias" voltages may be supplied by dry-cell batteries (see Arts. 62-64), but it is more common to employ specially-designed mechanical-vibrator and transformer arrangements, dynamotors, etc., for producing the high "plate" and "C"-bias voltages required. These devices also take their operating current from the storage battery of the car.

Since only a short antenna may be erected on the automobile, the signal pickup is rather weak (a few microvolts at best) and a very sensitive receiver is required. Also, the electrical, interference created by the ignition system of the automobile must be eliminated. Finally, the problem of providing satisfactorily tuning and volume controls within easy reach of the driver, must be considered.

527. Selection of the tubes: The filament current for the tubes is usually obtained from the same storage battery which is used for the ignition and lighting system of the car. Since the tubes used in receivers of this type must be able to withstand the continuous vibration of the car without shattering, they must be of rigid construction. Also, since the output voltage of the charging generator connected across the battery is a pulsating current, the filament current will also be pulsating while the engine is running. For these reasons, tubes of the separate-heater

type are desirable on account of the rigidity of their heaters and the freedom from electron emission variations. While both 6 and 12-volt types of batteries are used on automobiles, the 6-volt type is most common in American automobiles. Special separate-heater type tubes have been developed to operate satisfactorily from this source of filament voltage supply. Among these, are the '36 type screen-grid amplifier tube, the '37 type general-purpose tube, and the '38 type power output pentode tube, (see Fig. 214) which all operate with a filament voltage of 6.3 volts and a filament current of 0.3 amperes.

All are of the high-vacuum type, and they employ coated cathodes, indirectly heated. The cathodes, which are the same for all three tubes, have been carefully designed to insure uniform heating over as wide a range of heater voltage as possible, in order that the tubes will perform satisfactorily under the normal voltage variations of automobile batteries during charge and discharge. This feature, together with that



Courtesy The National Co

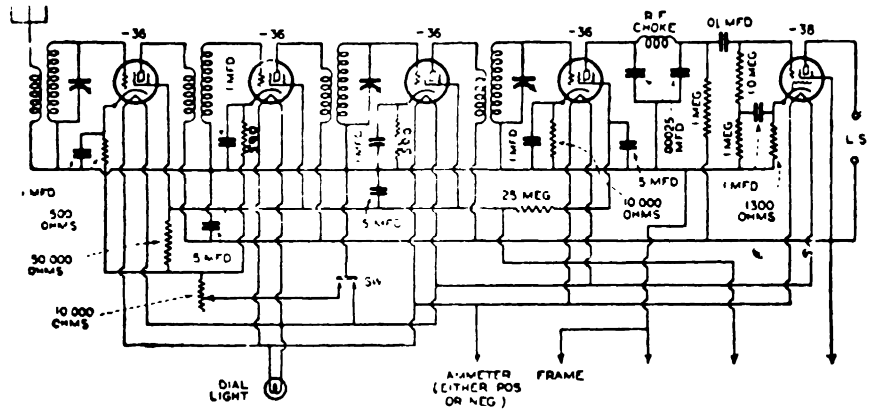
Fig. 392—Five tube t-r-f receiver designed for automobile installation. The receiver is shown mounted in place under the instrument board of the car, at the left It is enclosed in a dust-proof metal case A tuning dial is provided directly on the receiver The circuit diagram is shown in Fig 393.

of the general freedom from microphonic and battery circuit disturbances of the separate-heater type, make these tubes particularly well suited for use in automobile receivers. The '36 type screen grid tube may be used either as radio-frequency amplifier or detector. The heater voltage, which is obtained directly from the car battery, may vary between 5.5 and 8.5 volts during the charge and discharge cycles of the battery, without appreciably affecting the performance or serviceability of tubes. No resistor in the heater circuit is required when operated from a 6-volt car battery. If a battery of higher voltage is installed in the car, the voltage may be dropped to the proper amount by connecting a resistor in series with the circuit, its value being calculated by Ohm's Law ($R = E/I$).

528. The receiver: Since the signal pickup of the short, low antennas which must be used on automobiles is very small (being only a few microvolts at best), the receiver must be designed to be very sensitive, a sensitivity, such that the receiver will deliver a signal output of 80 milliwatts when a signal voltage of about 20 microvolts is applied to it, being considered satisfactory for most ordinary requirements. This performance must be obtained with economy of space, weight, and batteries.

Construction must be dust-proof, and sufficiently rigid to stand up well under the vibration existing in the car. Both superheterodyne, and t-r-f circuits are suitable for receivers of this type. A typical 5-tube t-r-f receiver designed especially for automobile installation is shown in Fig. 392. The installation of the receiver unit under the instrument board of the car is shown at the left. The "on-off" switch, tuning knob and volume control are plainly visible. This particular unit is constructed so it slides out of the container cabinet by unfastening four screws on the front panel. This facilitates tube replacements or testing. At the right, the chassis is shown removed from the container. The tubes, 3-gang tuning condenser, and dial are plainly visible. The circuit diagram of this receiver is shown in Fig. 393.

The receiver contains three stages of screen-grid tuned r-f amplification, a screen-grid power detector, and a power output pentode tube. The filaments are all



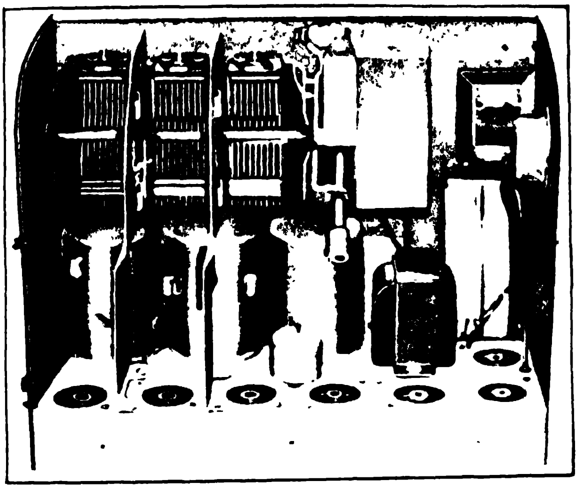
Courtesy Radio News Magazine

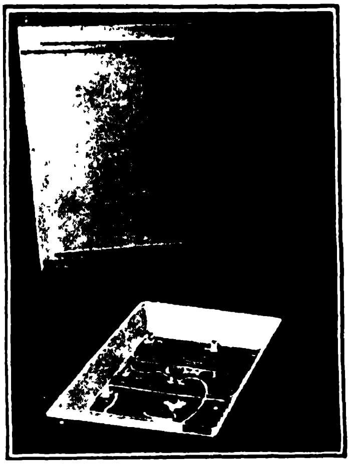
Fig 393 The circuit diagram of the automobile radio receiver which is shown in Fig 392 It is a 5-tube screen grid t-r-f receiver using a power pentode output tube All tubes are of the 6 3 volt filament separate-heater type

connected in parallel, one terminal going to the terminal of the ammeter on the instrument board of the car, and the other one connecting to the frame of the car, which is grounded to one side of the storage battery which is ordinarily used for ignition, starting and lighting current supply. Whether the positive, or the negative, terminal of the car battery is grounded to the frame does not matter. Grid bias voltages for the various tubes are obtained by the voltage drop through the various grid bias resistors connected in the cathode circuits as shown. The detector is resistance-capacity coupled to the '38 type pentode output tube. The use of the power pentode tube has the advantage that large output is obtained with relatively small signal voltage input to the grid. Only three leads run to the B batteries, one for the B— connection, one for the +67 volts for the screen grid circuits and one for the 135 volts for the plates. A 3-gang tuning condenser is employed, for single-dial tuning control. A double contact "on-off" switch which opens both the filament circuit and the main "B" or "plate" circuit is provided.

529. The loud speaker: From 2 to 2.5 watts of power are necessary for satisfactory reproduction in automobiles. Three types of loud speakers are suitable. They are, the "balanced-armature", the "inductor", and the "moving-coil" types. Cone diaphragms with a metal protecting

case are usually employed. The moving-coil type may have a field magnet of either the permanent magnet or electromagnet type. The field coil on the latter must be wound either to operate from the 6-volt storage battery of the car or to act as a filter-choke in the "B" power supply unit. Since only a small volume of sound is required in an automobile, the speaker really need not be of the types designed to handle large volume. The location of the loud speaker in the car has considerable effect on the resultant tone quality, and before definitely mounting the speaker in position it should be tried in several different locations. The location under the dash, commonly used in many installations, is one of the poorest places from an acoustic point of view, in which to place the speaker.





Courtesy Radio News Magazine

Fig 394—Left Interior view of the chassis of an automobile receiver designed for remote tuning control The shaft and coupling at the center, attach to the tuning-control drive-shaft
Right A "B" battery compartment consisting of a sponge-rubber lined metal box sunk into the floor at the rear of the automobile "B" batteries need not be employed, for satisfactory "B"-power supply units operating from the car storage battery are available

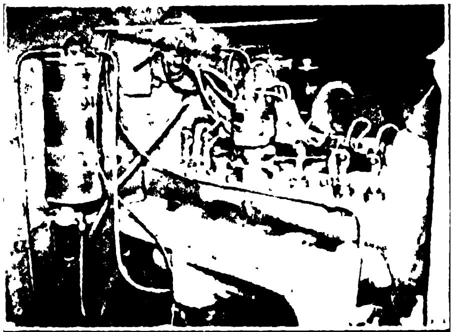
Mounting it under the roof of the car, at the center is preferable, but this requires a speaker of pleasing appearance and fairly flat construction.

530. The "B" batteries: When "B" batteries are employed, they are usually mounted in a suitable metal box, lined with sponge rubber at least 1/2 inch thick for protection against jolts. In touring cars and sedans, this box may be built into the floor at the rear; on the side of the car opposite that on which the exhaust pipe and muffler are located, for heat deteriorates "B" batteries. An installation of this kind is shown at the right of Fig. 394. In roadsters and coupes, there is generally ample space for the "B" battery box in the luggage compartment in the rear.

In making battery connections to the receiver, armored cable or miniature BX especially made for automobile wiring purposes, should be employed, and this metal covering should be grounded. Not only does this shielding of the battery wires reduce the ignition disturbances picked up, but it greatly decreases any possibility of

short circuits due to damaged insulation caused by shifting and rubbing of the wires, and consequent grounding of either the plate or filament circuits. Due to the use of the heater-type tubes throughout, polarity of the connections to the storage battery is of no consequence. A connecting plug into which the leads from the "A" and "B" batteries are terminated, is usually plugged into a socket provided at the side of the receiver box.

531. Tuning control: Two types of tuning controls may be used. One is the direct type shown on the receiver of Fig. 392, in which the tuning dial is mounted directly on the receiver cabinet. The other type, shown in the installation at the left of Fig. 395 employs a flexible drive



Courtesy Radio News Magazine

Fig 395—*Left.* Remote tuning control mounted on the instrument board of the automobile. The receiver and loud speaker are underneath
Right. Spark plug resistors in place on the spark plugs of a 6-cylinder automobile engine to suppress interference from the ignition system

member between the tuning control, which is placed in a location most convenient to the driver, and the tuning condenser drive on the receiver. This flexible drive member may consist of link-connected rods, a flexible cable or spring drive svstem, etc. This remote-control tuning provision enables the receiver to be mounted in the most suitable location, away from the tuning control if necessary, but adds to the cost of the outfit. In the receiver shown at the left of Fig. 394, and at the left of Fig. 395, a remote tuning drive is provided, the receiver controls being mounted on the instrument board, and the receiver and loud speaker being mounted out of the way under the cowl, as shown.

532. The antenna and ground system: Two types of antenna installation are in common use.

In one type, the antenna system consists of two flat metal plates about 8 × 30 inches each, which are mounted by insulators, beneath the running boards of the car. These two plates are connected together to the "antenna" terminal of the receiver. The "ground" connection is made to the metal frame of the car, this acting as a "counterpoise ground" (see Art. 615). This type of antenna has the important advantage of reduced ignition circuit interference pickup, since it is fairly well shielded from the disturbances radiated from the ignition system, but the radio-signal pickup is also rather law.

In the other antenna system, the antenna is installed in the roof of the car, above the roof upholstery. It may consist of a cloth-covered copper screen, "chicken-wire" metal screening, or a coiled loop of insulated flexible wire. A shielded lead-in wire is

usually brought down through one of the hollow front posts of the car body, for connecting the antenna to the radio receiver.

Many cars are equipped with built-in antennas in the factories, when they are assembled. Generally, these antennas consist of metal screen-mesh located above the upholstery in the roof of the car. While it is not an impossible task for anyone to remove the roofing material and install such an antenna, a much simpler method in a used car, is to obtain a large darning needle and some fine flexible wire and thread the wire through the roof upholstery forming a coiled-wire antenna.

In roadsters and touring cars, a flexible wire may be stitched into a piece of cloth, to form a horizontal coil. This unit is then stitched to the pads which support the "top" material at each side. A lining of the same material as the top, is stretched beneath to conceal it from view. In such an installation, the top may be folded back, as the lead-in wire is brought down from the rear of the top, and along the body-sill to the cowl. The set may be operated with the top up or down, although better reception is of course had with the top up. Measurements of these screen-type antennas show, for sedan models, a capacity of about 200 $\mu\mu$f. and a resistance of about 1.5 ohms at 1,000 kc. The inductance is negligible. This capacity compares favorably with that of a good broadcast antenna, but the effective height averages but .4 meter, which means that the signal voltage pickup is very weak (a few microvolts at best), and a very sensitive receiver is required.

533. Ignition system interference: Unless suitable precautions are taken in the design and installation of automobile radio equipment, objectionable noises due to electrical interference from the ignition system of the engine, will result.

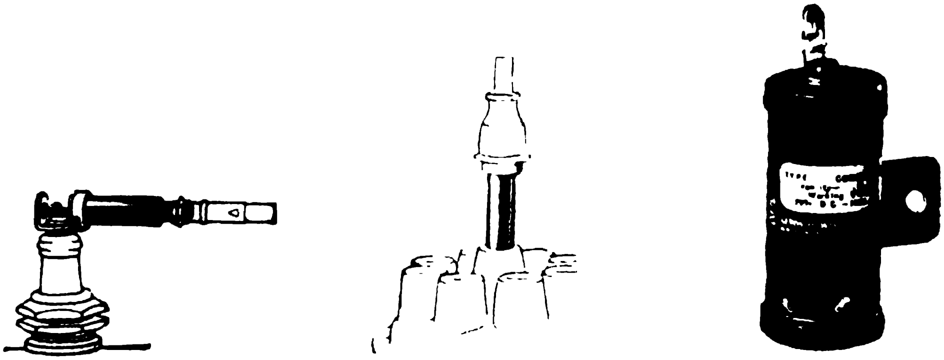
The high-tension ignition wires of a gasoline engine may be considered as miniature antennas, grounded at the spark-plug end and oscillating at a frequency dependent upon their distributed inductance and capacity, practically determined by their length. The passage of the spark at the plug, excites these miniature antennas, and as their radiation efficiency is high, a considerable amount of power is radiated. Owing to the high radiation resistance, damping in these circuits is also high and the energy thus radiated in highly damped trains impacts the antenna used for the radio receiver. Each time a spark plug fires, a clicking noise sounds in the radio receiver. The resultant interference is similar to that experienced by broadcast receivers from 600-meter spark transmitters of high decrement. In the car however, the interfering damped train from the ignition system has a frequency lying between 10 and 60 megacycles, in some cases higher. Also, coupling is much closer. The spark plug wires could be shielded by a grounded metallic shielding, but this would materially complicate the ignition system, and is not really necessary. The oscillatory character of the currents in the ignition wires may be destroyed by connecting sufficient resistance in each oscillatory circuit so as to make it aperiodic. Each spark current then becomes a single pulse instead of a train of damped waves. In practice it is customary to connect a resistor of from 10,000 to 25,000 ohms directly in series with each spark plug lead (at the plug), to accomplish this. The introduction of resistance, even in the order of several thousand ohms, in series with the very high resistance of the spark gap before rupture does not appreciably affect the *total* resistance of the circuit and will have no effect on the spark. It will however, rapidly dissipate the energy fed to the circuit by the spark coil after the rupture has occurred, thus dissipating this energy as heat, rather than radiating it at radio frequencies.

Suitable carbon-type resistors designed especially for connection to each spark plug are employed. A typical resistor of this type, fastened to the spark plug terminal, is shown at the left of Fig. 396. The installation of the resistors on the spark plugs in an actual engine, is shown at the right of Fig. 395. Spark plugs of special construction, in which the resistance element is already included in the center of the usual porcelain insulator are also available and are used extensively.

In a gasoline engine, the wires directly associated with the spark plugs are not the only source of radio-frequency disturbances.

These wires terminate at the distributor, which is in reality a rotary switch. The center rotor of the distributor is fed from the high-tension terminal of the spark coil. This "rotor" is separated from the various contacts by a definite gap, and this gap is important, being placed there for a particular purpose. If a plug is "fouled" because of carbon deposits, the resistance of the circuit in the plug can no longer be considered infinite, but assumes a high value, generally several megohms. The high-potential current induced in the coil secondary would leak thru this resistance rather than rupture the gap in the plug. The purpose of the distributor rotor clearance, then, is to permit the secondary current to build up to a fairly high potential before passage to the spark plug, thus insuring a spark even though the plug be partially shorted by the resistance due to fouling. A resistor must therefore be inserted in series with the lead to the distributor brush, in order to destroy such oscillation as may occur in this lead. A resistor for this purpose, which plugs directly into the middle terminal of the distributor cap, is shown at the center of Fig. 396.

With the elimination of the high-tension circuit interference, the major source of trouble is overcome. However, electrical interference may still be present, caused by



Courtesy Allen Bradley Co *Courtesy Aerovox Wireless Corp*

Fig 396—Left A resistor in series with the spark plug for suppressing the oscillations in the spark plug circuit
Center A resistor in series with the high tension lead of the distributor for the same purpose
Right A special heat-resisting by-pass condenser for use in ignition interference suppression systems on automobile radio receiver installations

various elements of the low-tension circuit. The primary of the ignition coil still causes trouble, owing to the oscillatory nature of the break at the timer points.

The frequency of these disturbances is rather low, seldom higher than about 2,500 cycles, but it can find its way to the audio system of the receiver via the filament circuit. This may be overcome to a great extent by connecting a condenser of 1 to 2 mf. capacity between the battery side of the coil, and the ground, so as to provide a short low-impedance by-pass path for these oscillations. It also prevents any r-f impulses which may be developed at the breaker points, from travelling back through the primary wiring of the car to the storage battery and to the filament circuit of the receiver.

Electrical disturbance from the generator is often very noticeable. A 1 or 2 mf. condenser connected directly across its brushes, will clear up any but the most perverse ripples. If this is insufficient, the generator must need attention. A dirty commutator, badly-fitting brushes, or open bars will cause brush sparking which is noticeable in the radio receiver. The radio receiver thus serves as an excellent check on the condition and operation of the generator.

A simplified schematic diagram of a complete automobile ignition system for a four-cylinder engine is shown in Fig. 397. The location of the various "suppressor" resistors and the generator by-pass condenser are indicated on the diagram. Since the generator by-pass condenser must be able to withstand the rather high temperature existing under the engine hood, it should be impregnated with a wax of high melting point. A

special metal-enclosed condenser of this type designed to withstand temperatures up to 160 degrees F. is shown at the right of Fig. 396.

534. Aircraft radio receiver requirements: Two-way communication between aircraft and ground stations is becoming a very important essential to safe flying. The value of such equipment for the purpose of obtaining reliable weather reports, landing field condition reports, radio beacon signals, and for emergency work, cannot be too strongly realized. The requirements of radio equipment to be used on aircraft are rather severe.

The dominating requirements are, of course, light weight and small size. Not only must the set be small and light, but the accessories, such as batteries, must be compact and light, too. The airplane receiving set must be made so that it can be placed anywhere on the "ship," in some cases with remote controls to operate it. It also must have great sensitivity variation because it is changed in location so rapidly, from nearness to the sending station to a distance from it. In open-cockpit planes, the tuning controls must be such as to permit operation with heavy gloves on, at times. A locking device is frequently necessary to prevent "creeping of tuning", due to vibration of the plane, especially for beacon work. The apparatus must be able to withstand the unusual climate, humidity, and temperature changes encountered during any kind of flight, and must stand up under the continuous vibration caused by the engines.

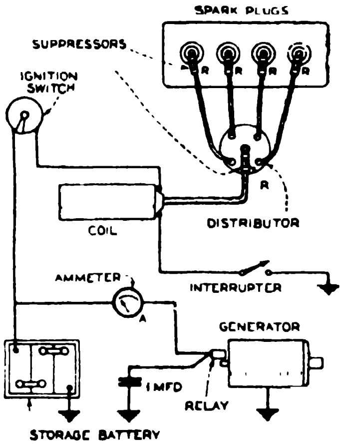


Fig 397—Simple schematic diagram of the main parts of an automobile ignition system showing how the spark plug and distributor "suppressor" resistors, and the generator 1-mfd by-pass condenser are connected to eliminate interference in the radio receiver

535. Engine ignition interference: As aircraft engines use ignition systems with spark plugs, such as are employed in automobiles, the receiver itself must be thoroughly shielded and proper steps must be taken to eliminate the radiation of radio-frequency fields from the ignition wiring and the magnetos which are commonly used as the source of e.m.f. for the ignition system. Since very sensitive receivers are generally used in aircraft, it has been found necessary in most cases, to employ elaborate shielding harnesses for both the spark plugs and the high-tension wiring, and to bond all the bracing wires and cables in the ship. in order to prevent discharges of static electricity generated by metal parts rubbing on other surfaces. All wires in the ship are either shielded with copper braid or else run in conduit. The latter method is preferable, where possible. When the ship is equipped with a high-frequency transmitter, all wiring is generally completely enclosed in grounded shielding, to prevent it from absorbing the radiated energy from the transmitter.

536. Shielding the ignition system: The shielding of the entire magneto is a relatively simple matter. A typical shield for this purpose is

shown in Fig. 398*. It consists of two aluminum sheets bolted to the magneto, and a band of spring bronze which covers the gap between the plates. A removable block with the wire outlet tube, fits in front. All of the ignition wiring is also shielded, a complete harness being made up for this purpose, as shown in Fig. 399.

Ordinary braided shielding alone over the wires is not effective, because when oil soaks into the braid, it insulates each strand from its neighbor enough to impair the

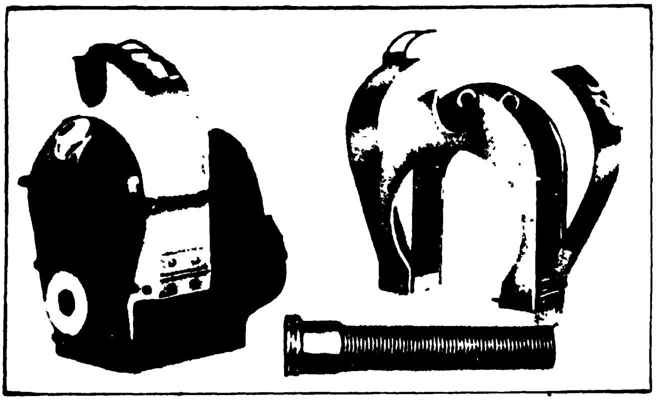


Fig 398 — Magneto shield developed for confining the r-f radiations set up by the magnetos on aircraft engines At the left, the shield is in place on the magneto At the right, it is removed and opened. The high-tension ignition wires are led out through the metal tube shown at the bottom.

Courtesy Mr. R. H. Freeman and Aeronautical Eng. Magazine

effectiveness of the shielding. The shielding harness consists of two main tubular aluminum rings in which the wiring is placed. One ring carries the wires for the front spark plugs, and the other one placed at the rear of the motor carries the wires for the rear plugs. Branching off from these rings are flexible oil-proof shielded leads running to the spark plugs, and large flexible tubing to the magnetos. The in-

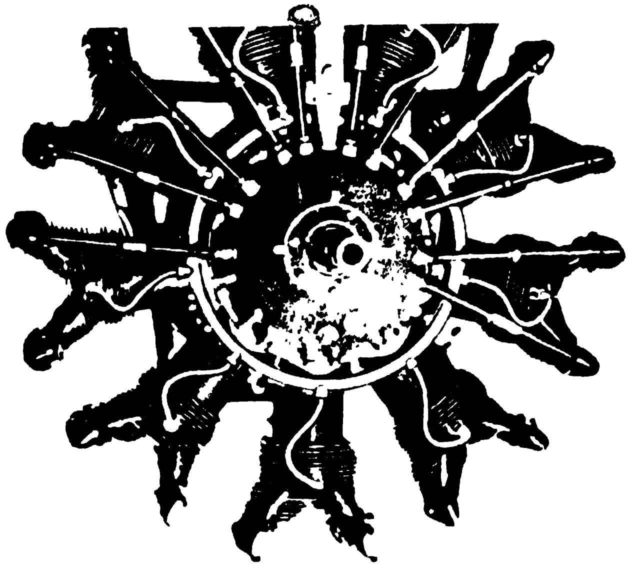


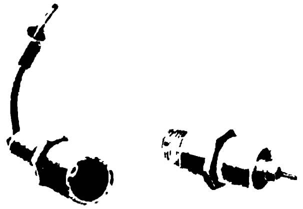
Fig. 399 — Complete "harness" for shielding the ignition wires running to the front spark plugs of an aircraft engine. All of the wires run inside of it. A similar harness is at the rear of the engine for the wiring to the rear spark plugs. Notice the short flexible leads from the tubular ring to the individual spark plugs.

Courtesy Mr R H. Freeman and Aeronautical Eng. Magazine

*From an article on Commercial Aircraft Radiophone Communication by Robert Freeman, in Vol. 3, No. 2 issue of Aeronautical Engineering Magazine.

sulated ignition wires run inside of the shielding. A typical complete harness mounted on a radial aircraft engine is shown in Fig. 399. Each spark plug is shielded by a metal shield cap with prongs which fit down over the plug sleeves and clamp into the groove at the base of the nut by spring action. At the top of the cap there is a gooseneck which reverses the direction of the wire in rather a short arc and leads it back toward the direction of the harness. Inside the cap there is placed an insulating sleeve which fits down over the center electrode of the plug, inside of the nut sleeving. This forms a long path for the electrical energy to jump across or leak through. A small spring and screw in the top of the insulator, connect the top of the plug to the wire entering the cap. The shielded spark plug, gooseneck and insulator of this type are

Fig 400—From left to right are shown the gooseneck and metal shield cap, shielded spark plug, spring, and special hollow insulating sleeve which are used in the shielding arrangement of Fig 399.

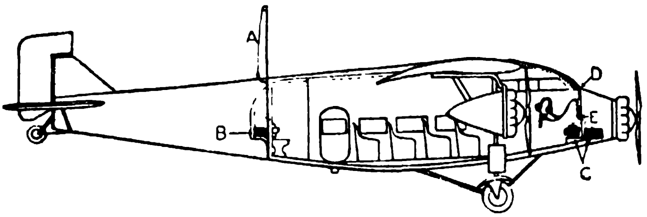


Courtesy Mr. R. H. Freeman and Aeronautical Eng. Magazine

shown in Fig. 400. In this way a complete covering of metal for the ignition system is provided, which suppresses the interference to a point where it is not audible in the receivers.

537. The antenna system: The trailing-wire type of antenna, which has been used until very recently for both the dirigible type of airship and the heavier-than-air type of craft, has several distinct advantages as well as disadvantages. Its use is confined largely to the lower frequencies, and it is comparatively satisfactory around 300 kc.

It is possible with this type of antenna to communicate over comparatively long distances with a minimum of power. However, it is necessary to reel it out when



Courtesy Radio Craft Magazine

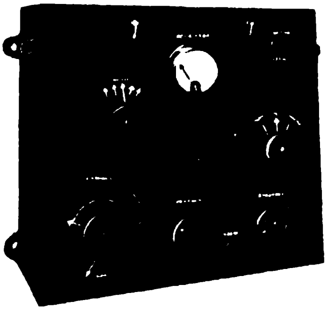
Fig. 401—Arrangement of radio transmitting and receiving equipment on a large passenger plane The receiving antenna "A" comprises a length of wire supported on a streamlined strut; "B" is the radio receiving set; "C" is the dynamotor and battery, "D" is the remote tuning control dials at the pilot's seat, "E" is the remote volume control, and "F" indicates the headphones

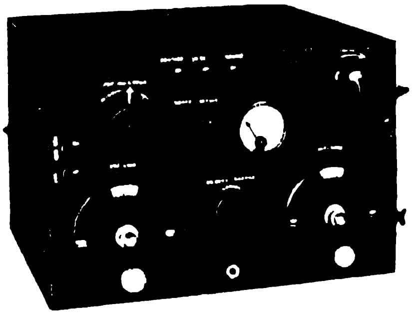
communication is desired and to reel it in when communication is finished. The maintenance cost of this type is large, and the hazards encountered when flying at low altitude make it undesirable. It is also impossible to use it when a forced landing must be made. Its air resistance increases the drag on the ship and materially reduces its speed. It is impractical for military use, as a plane cannot be stunted with it. A short vertical "rod" or "strut" antenna is commonly used instead. This consists of a streamlined duraluminum vertical antenna rod A about 6 feet in height, mounted vertically on top of the fuselage, away from the direct radiation field of the ignition

wiring as shown in Fig. 401. In those cases where radiation is required for transmission, two wires may be run from the front-wing spar on either side to the top of the mast and then back to the vertical tail fin. With this antenna, transmission can also be carried on while the plane is on the ground. The engine frame and the bonded bracing wires in the wings and fuselage act as the counterpoise ground.

538. Radio equipment: The type of transmitter used in aircraft depends upon many factors. The transmitters are built compactly, and of light weight.

A range of at least 100 miles of consistent communication is acceptable for commercial aircraft flying along standard airways, since stations are located every 200 miles, and beacon marker stations with auxiliary





Courtesy Allen D. Cardwell Mfg Co

Fig 402—Left U S Signal Corps aircraft code and phone transmitter
Right U S Navy aircraft receiver

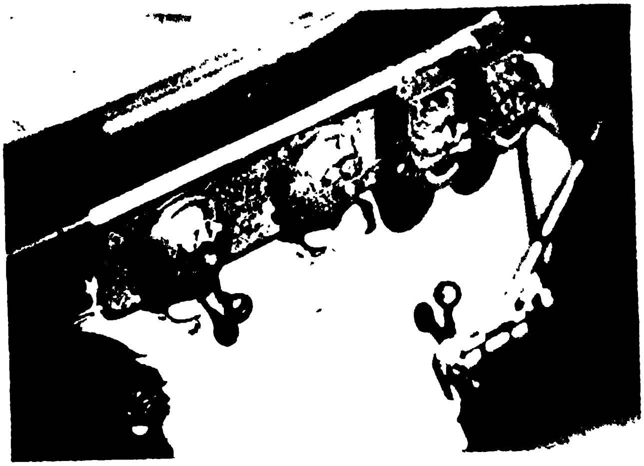
equipment every 100 miles. A combined CW and radiophone transmitter seems to be the desirable thing, because few pilots have the time or patience to learn the code sufficiently for expert operation of a straight CW transmitter. Special microphones designed to eliminate outside noises are employed. These fasten to the helmet of the pilot, together with the light-weight earphones built into the helmet.

The matter of filament and plate power supply for radio transmitters and receivers seems to be very much an open question. Batteries are heavy and a sufficient number cannot be carried for transmission purposes. A dynamotor, which is in reality a motor-generator, is very inefficient because the current that is used must first be supplied at low voltage by a storage battery and translated from electrical to mechanical energy and back again at a higher voltage in the dynamotor. There is an extra loss of efficiency in going through the dynamotor which can and does add both weight and power to the equipment that is needed. A wind-driven generator cannot be used, because its driving propeller becomes unbalanced with a coating of ice in winter often tearing the generator loose from its mounting. The double-voltage generator which converts mechanical energy directly into the two voltages needed for filament and plate supply seems to be the proper answer. A clutch and a third winding on the armature will permit its being used as a dynamotor on forced landings for power supply when the motor is dead. It may then be operated from a small emergency battery. It is true that there are still some mechanical difficulties with the double-voltage generator, but it is felt that these can be eliminated. It is the lightest combination available that will provide the necessary power for the radio transmitter. A special voltage regulator which is provided, keeps the output constant.

A typical aircraft transmitter for both code or radiophone transmission is shown at the left of Fig. 402. This is used by the U. S. Signal

Corps. A form of aircraft receiver used by the U. S. Navy is shown at the right. In large passenger and mail planes, the transmitter and receiver are installed usually in the tail end of the fuselage or in a compartment directly behind the main passenger compartment. Flexible shafts connect the tuning condenser shafts of the receivers with remote control dials in the pilot's cockpit. The arrangement of the remote tuning and volume controls at the left side of the open cockpit on a mail plane are shown in Fig. 403.

539. Radio beacons: The radio beacon for guiding aircraft, has been perfected so that it is as practical and perfect as the ordinary mag-



Courtesy Mr. R H Freeman and Aeronautical Eng. Magazine

Fig 403—Remote tuning and volume controls for the radio equipment on a mail plane. These are mounted at the left side of the cockpit within easy reach of the pilot. Notice the lever-type controls to permit of easy handling by the pilot even though he may be wearing thick, heavy gloves

netic compass. The loop or coil form of antenna has the peculiar property of directional reception and transmission which makes it invaluable in radio beacon work.

In directions toward which it points, reception is good. At right angles to its plane, reception is practically zero. When a loop antenna is used for transmitting, a similar effect is noticed. The radio range beacons in service in American airways rely upon this principle. However, two loop-type transmitting aerials are used at the airport, at right angles, or at different angles with each other in accordance with the nature of the course. A remarkably ingenious system is used to enable the pilot to maintain his direction. One loop aerial is continuously sending out a certain radio code signal by a mechanical device, say a dash and a dot, and because of the characteristics of the loop aerial, this particular combination goes out in the general direction of North and South or East and West, as the special position of the course requires. The other loop aerial is sending out another complimentary combination of dots and dashes which exactly fit in between those of the first aerial. The plane has a separate receiving loop antenna mounted on the end of each wing. Therefore, when the plane is headed directly along its proper course toward the transmitting station, its receiving loops receive an equal amount of energy from each of the transmitter loops. Since the signals transmitted by the two transmitter loops are complimentary, the fact that they are received with equal loudness causes them to fit in with one another so that the pilot is unable to distinguish either the dot-dash combination or

the dash-dot combination, and instead, he hears only a continuous dash or sound, as long as his plane is headed properly along the course.

This condition of equal loudness occurs only along a very restricted path pointing straight toward the beacon, so narrow in fact, that at a distance of 100 miles, the path over which the two signals blend perfectly is only 6 miles wide. As the pilot flies toward the beacon he is able to correct his course constantly, for if the plane gets off to one side, his radio set picks up the signals from that side with greater volume than from the other side and he instantly knows which way to turn. As he gets nearer to the beacon, the course narrows greatly, guiding him directly to the airport.

The radio beacons use frequencies in the band from 285 to 350 kilocycles (corresponding to about 857 to 1,052 meters). Originally, different groups of dots and dashes were used, but it was found that the pilots got better results with the N and A (dash-dot and dot-dash) combinations. To identify which station is being received aboard the plane, a number of combinations forming a single group (with a pause between each group) is employed. In addition. every 15 minutes the station switches over to a microphone and an announcer gives the call letters and name of the station, and also weather and wind conditions and forecasts.

REVIEW QUESTIONS

1. How do the operating conditions for radio receivers operated in automobiles differ from those in home receivers?
2. Explain the requirements as regards sensitivity, size, weight, battery current consumption, etc., which a satisfactory automobile radio receiver must meet.
3. Explain how it is possible to operate a radio receiver in an automobile in which no connection is made to the earth, since the rubber tires on the automobile insulate the chassis from the earth.
4. Describe two forms of antenna installations in automobiles.
5. Explain how the high-tension circuits in the ignition system of a gasoline engine, create interfering electric disturbances which radiate from it. How may these disturbances be reduced effectively in automobile radio installations?
6. Explain how the low-tension circuits in the ignition system create interference, and how this may be prevented.
7. Explain how the battery-charging generator on the car may cause interference and how this may be prevented.
8. Why is it desirable to run all battery wiring in an auto-radio receiver installation in metal conduit grounded to the frame of the car?
9. Why is the signal pick-up of the average antenna installed in an automobile very small? Of what importance is this?
10. If the filament-current drain of the receiver were causing the storage battery to operate in a discharged condition most of the time, would increasing the charging rate of the generator help any? Explain!
11. Explain the advantages obtained by using, (a) separate-heater type tubes; (b) screen-grid amplifier type tubes; and (c) power pentode output tubes, in automobile radio receivers.

12. How is the electrical interference from the ignition system of aircraft engines effectively suppressed, to permit satisfactory operation of extremely sensitive radio receivers? Why are these extreme precautionary measures not usually necessary in automobile radio installations?
13. Describe the elements and operation of the radio-beacon system used for guiding the flight of aircraft.
14. Why must aircraft receivers and transmitters be designed ruggedly, and of lighter weight and greater dependability than similar equipment used on the ground?
15. How is it possible to receive radio signals in an airplane, when the earth may be several thousand feet below it, and no "ground" connection to the earth is possible?

CHAPTER 30

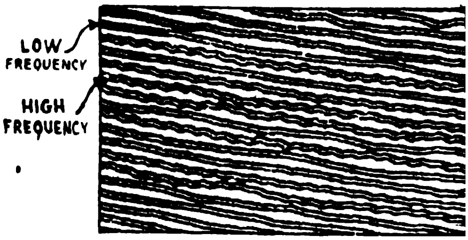
PHONOGRAPH PICKUPS AND SOUND AMPLIFIER SYSTEMS

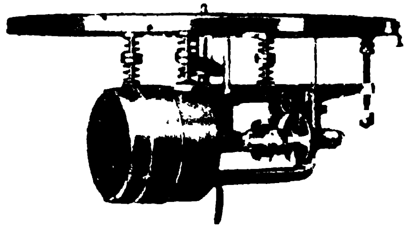
PHONOGRAPH RECORDS — THE ELECTRICAL PHONOGRAPH PICKUP SYSTEM — THE ELECTRICAL PHONO-PICKUP UNIT — THE OIL DAMPED PICKUP — VOLUME CONTROL — SCRATCH FILTER — CONNECTION TO RADIO RECEIVER — HIGH IMPEDANCE AND LOW IMPEDANCE PICKUPS — SOUND AMPLIFIER SYSTEMS — THE AMPLIFIER — MICROPHONES — MIXING PANEL — THE LOUD SPEAKERS — HOME RECORDING — REVIEW QUESTIONS.

540. Phonograph records: The popular phonograph record of today is made by recording sound vibrations on a circular disc of suitable material. The disc contains a continuous spiral groove in which the needle of the reproducer unit runs while the record revolves. In records for home use, the reproducer is started at the outside edge and runs toward the inside of the disc. In records used in sound picture work, the reproducer starts at the inside and moves toward the outside edge of the disc. The spiral groove contains little waves or ripples all along it, whose wave-form corresponds to the wave-form of the sound recorded. In the *laterally-cut* type record which is used almost entirely nowadays, the spiral groove is of practically constant depth and cross-section, having a spacing between adjacent turns or spirals of the groove, of about 1/100 of an inch. However, the groove has little horizontal wiggles or waves in it, whose wave-form corresponds to that of the original sound, and whose frequency at any instant (provided the record is rotated at the proper speed) corresponds to the frequency of the sound. If we were to look at the grooves of a phonograph record under a powerful magnifying glass, they would appear somewhat as shown at the left of Fig. 404. Notice that the grooves are all of constant width. For a high-frequency note recording, the groove has many short wiggles following each other closely. For a low-frequency note recording, the wiggles are long and not so frequent. The student is urged to inspect with an ordinary reading glass or other magnifying glass, the grooves in a phonograph record containing low-frequency recordings. It is evident that any device which is placed in, and made to follow, the groove while the record is revolved at the proper speed, will be forced to vibrate back and forth sideways, as it follows the waves or wiggles in the groove. The *amplitude* of its vibration will correspond to the amplitude of the wiggles, and the *frequency* of its vibration will correspond to the number of the wiggles (in the groove), which come past the device every second. Of course, this depends on the speed at which the disc

is rotated, so that if the sounds are to be reproduced at their proper frequency, the record must be rotated at the proper speed. The usual phonograph disc record is designed to be revolved at 78 revolutions per minute. The 12-inch record plays for four minutes, while the 10-inch record plays but 2½ minutes. The 16 inch records used in sound picture work, in sound amplifier systems, and for broadcasting purposes (electrical transcriptions) revolve at 33⅓ r.p.m. and play for about 14 minutes.

Experiment: Play a phonograph record at its proper speed. Now slow up the disc gradually by pressing your hand against the turntable. Notice that the tone becomes lower and lower, since the wiggles in the groove are not going past the needle in the reproducer as fast as they should, and therefore the needle is not vibrated as fast is it should be. Now place a small strip of paper under the record so its end projects out and is visible. Set the record in motion, and count the number of revolu-





Courtesy Pacent Elect Co

Fig 404—Left How the wiggles in the grooves of a portion of a phonograph record appear when observed under a magnifying class The needle-point running in the groove, vibrates from side to side due to these wiggles A high-frequency recording consists of short wiggles close together In a low-frequency, recording the wiggles are long and far apart, as shown
Right A side view of a typical induction type a-c elctric spring mounted phonograph motor and the turntable

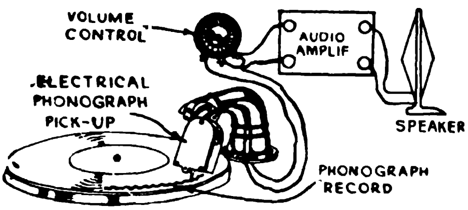
tions it makes in one minute, by noticing the seconds hand on a watch. The regulation on the motor may be adjusted until the disc rotates at the proper speed in accordance with the figures given above. Now place the end of your thumb-nail, or the corner of a piece of thin stiff paper, in the groove while the disc rotates. Notice that the music is reproduced faintly by the vibrations of the nail or paper caused by the wiggles in the groove.

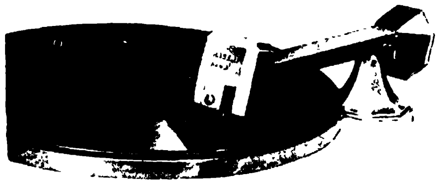
Phonograph records may be rotated either by the old-fashioned mechanical spring-type motor, or by the more modern electric motor drive which does not need to be re-wound after playing a record. A spring-mounted motor of this type with the turntable, is shown at the right of Fig. 404. Units of this type usually consist of an induction type a-c electric motor and a turntable, equipped with an automatic trip-stop and having a brake and switch arranged for either manual or automatic operation. The motor is provided with a simple speed regulation adjustment. Induction type motors are employed almost exclusively, since they have no brushes or commutator, and therefore do not cause electrical disturbances which might affect the radio receiver

541. The electrical phonograph pickup system: In the old mechanical type of phonograph. the reproducer head was arranged so that the sharp point of the needle, following the wiggles in the spiral grooves of the record, transmitted its vibrations to a flat diaphragm which produced corresponding vibrations (sound waves) of the air in the "sound box".

In the usual form of *electrical phonograph pickup unit* as shown at the right of Fig. 405, the vibrations of the needle are made to generate an e.m.f., whose value varies in exact accordance with the amplitude and frequency of the wiggles of the groove which go past the needle point. This induced e.m.f. is fed to the input terminals of an audio-frequency amplifier. This amplifies the audio-frequency variations of this e.m.f. until they are of sufficient strength to operate one or more loud speakers. In this way, the sound may be amplified to almost any intensity desired, and splendid reproduction is possible. The audio amplifier and loud speaker employed, may be a separate amplifier and speaker as shown at the left of Fig. 405, or the ordinary a-f amplifier and speaker which are already present in the home radio receiver. In the latter case, suitable provision is made, either by a switching arrangement or an adapter plugging into the detector tube socket, for connecting the a-f amplifier either to the phono-pickup unit or to the r-f amplifier and detector for either phonograph or radio reproduction. Most modern radio receivers are provided with suitable terminals for connecting the phono-pickup unit to the audio amplifier.

542. The electrical phono-pickup unit: A *phonograph pickup unit* may be defined as an electromechanical device actuated by the phono-





Courtesy Pacent Elect. Co

Fig 405—Left Electric phonograph-reproducing system The variations in the e m.f. generated in the pick-up are amplified by the a-f amplifier, and reproduced as sound waves by the loud speaker
Right A typical magnetic type of phonograph pick-up unit with the needle in place in the groove of the record The arm and head are counterbalanced by the weight at the right

graph record and delivering power to an electrical system, the wave-form of the voltage or power delivered to the electrical system corresponding to the wave-form existing in the grooves of the phonograph record. Phono-pickups operating on several different principles have been developed. Among these are the condenser type, the carbon resistance type, and the magnetic type. The latter is used almost exclusively, on account of its commercial practicability due to its high voltage output, comparative freedom from extraneous noises and simple mechanical construction, and the fact that its frequency-response characteristics may easily be modified to compensate for those of the record or amplifier systems so as to produce a satisfactory overall response. The magnetic pickups are of two types: *rubber-damped* and *oil-damped.*

The construction and operation of the simple reed-type rubber-damped magnetic pickup may be seen from Fig. 406. As shown at (B) and (C), a strong magnetic field is provided by a small permanent horseshoe magnet, having pole pieces of suitable shape fastened to it. Fitting between these pole pieces is a small coil containing several thousand turns of very fine enameled copper wire. Attached to the needle which runs in the record groove, is a small iron reed or armature which is pivoted, and placed within the hollow center of the coil between the pole-pieces, as shown. The pickup is placed over the phonograph record, in such a direction that the wiggles in the record groove cause the needle point to vibrate rapidly from side to side as shown by the dotted line positions at (A). On account of its large inertia, the pickup head

itself does not vibrate. The amplitude and frequency of the movements of the needle point, depends on the amplitude and frequency of the wiggles in the groove.

Just how this motion causes an e.m.f. to be induced in the coil may be seen from Fig. 407. Here the gap between the pole pieces has been drawn exaggerated, and the rubber damping blocks are not shown. The iron armature serves as a good magnetic path for the lines of force to travel through between the pole pieces. Remember that it is placed inside of the coil of wire, so any lines of force through the armature are

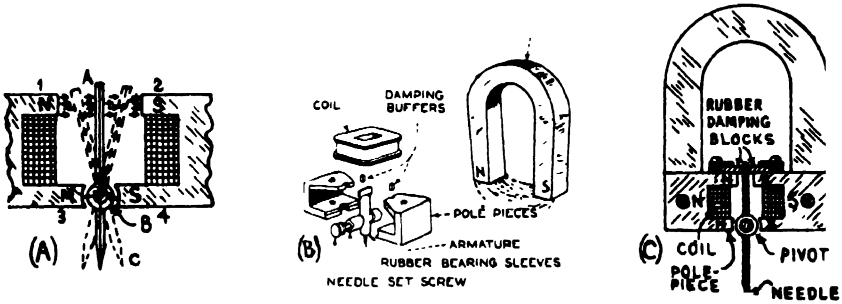


Fig 406—The arrangement of the various parts in a typical magnetic type phonograph pick-up with rubber damping. (A), Various positions which the needle and armature take during the playing of a record (B), The parts of a phono-pickup unit separated (C), The parts all assembled together.

really threading through the coil. When the armature is in the extreme position shown at (A), some of the lines of force of the permanent magnet are diverted from their normal path straight across the gap, and go from pole piece No. 1, *down* through the armature to pole-piece 4 and around through the magnet. They take this path because the iron armature presents a better magnetic path than the air gap across from 1 to 2. If the armature now returns to its vertical position as shown at (B), the air gap from 1 to A is increased. Therefore the field through the armature down to 4 weakens, and a greater part of the field goes directly across to 2. The main point to remember is that movement of the armature from the position at (A) to that at (B) has weakened the field through it, i.e., has changed the number of lines of force threading through the center of the coil. Therefore according to the laws of electro-magnetic induction, an e.m.f. is induced in the coil. When the armature moves to

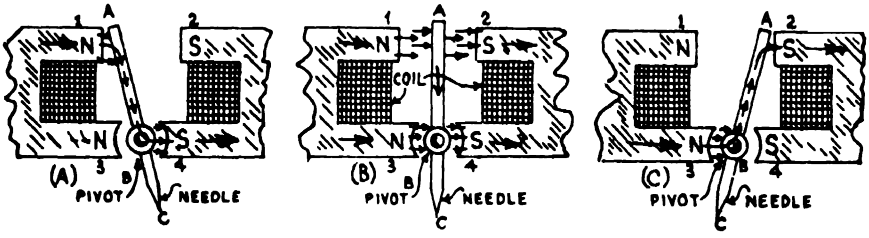


Fig 407—The movement of the needle and iron reed or "armature" in the phonograph pick-up unit, varies the magnetic flux through the coil and so induces an e.m.f in it. The path of the magnetic lines of force is shown here for three positions of the needle and armature

the extreme position at (C) the lines of force through it actually reverse in direction, now going up through it from the N pole piece No. 3 to the S pole piece No. 2 as shown. This causes another change in the flux, and since the flux through the coil is now in the reverse direction, the e.m.f. induced by it is also reversed. Consequently a complete vibration of the armature, such as might be caused by say a sine-wave wiggle in the record groove, would cause an e.m.f. of the same sine-wave form and frequency to be induced in the coil. When the record is being played, the armature is vibrating back and forth rapidly as shown at (A) of Fig. 406, and the induced e.m.f. is varying likewise. The two terminals of the coil are led out to the input terminals,

of the audio amplifier which amplifies the a-f voltage variations. The output voltage of the coil differs in pick-ups of different manufacture, being anywhere from a half volt to over 5 volts. The types delivering the higher voltages are especially suitable for operation with the single-stage audio amplifiers being employed in modern electric receivers, the single audio stage amplifying the output of the phonograph-pickup sufficiently to bring it up to good loudspeaker volume.

In most pickup units the weight of the pickup head, which contains the somewhat heavy permanent magnet, pole pieces, and the coil and armature, is partly counterbalanced by a weight at the other end of the arm (on the far side of the arm swivel), so the needle does not press down too heavily on the record and cause excessive wear of both the record and the needle. The vertical unit pressure between the needle point and the record is astoundingly great, due to the fact that the weight rests on the very small area of the needle point. Assuming the diameter of the needle point bearing surface to be .003 inch, and the needle pressure 5 oz., the resulting vertical unit pressure is roughly 44,000 lbs. per square inch. The counterbalancing weight may be seen at the right end of the pickup in Fig. 405. It is not desirable to completely counterbalance the weight of the pickup head and arm, for some weight must act on the needle in order to keep it from jumping out of the groove when loud low-frequency notes are played. As a consequence, records must be made of hard material, and they must be abrasive enough to grind the needle down a bit during the first few revolutions, in order to reduce the unit pressure at the needle point.

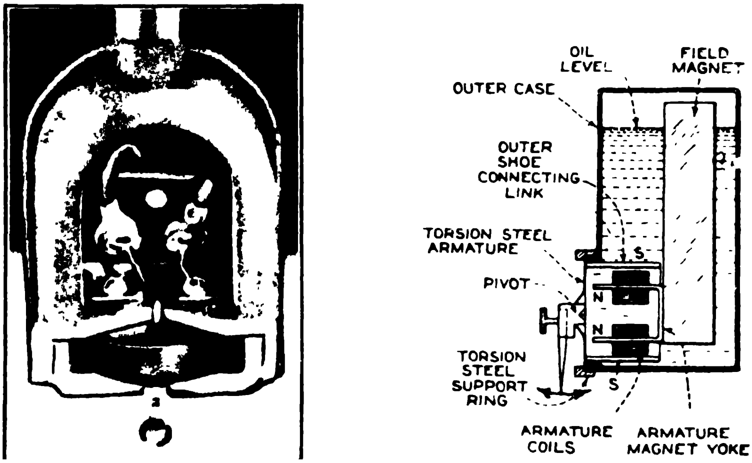


Fig 409—Left Interior view of rubber-damped magnetic pick-up unit with cover removed The horseshoe magnet, pole pieces, armature, and coil are plainly visible Right Cross-sectional view of a typical oil-damped pick up, showing the relative arrangement of the parts

The frequency characteristics of a pickup are almost wholly dependent on the character of the reed or armature, which makes up, with the needle, its simple vibrating system. A reed set in motion manifests a certain resonance frequency. In the best modern pickups, this resonance point usually lies between frequencies of 3000 and 4000 or over. In order to prevent an excessive response at these frequencies, it is necessary to damp the system. This is usually accomplished by means of rubber buffers applied to the free end of the armature. These buffers serve also to center the armature in the magnetic air-gap.

543. The oil-damped pickup: The oil-damped pickup, a cross-section view of which is shown at the right of Fig. 409, possesses frequency-response characteristics which are superior to those of the common rubber-damped type just described, and is used extensively in sound-picture reproduction, and in high grade sound amplifier systems.

As shown at the right of Fig. 409, a horseshoe field magnet (shown in side view) is arranged with an outer shoe and an armature magnet yoke with two windings on its leg. If the former is a S pole, the latter is a N pole as shown. Mounted near the poles is a thin steel armature fastened to the needle and pivoted at the center. Movement of the needle point causes torsional movement of this armature, thus varying the air-gap between it and the N poles, and consequently varying the magnetic flux threading through the armature magnet yoke and the coils. This induces a varying voltage in the coils. The case is nearly filled with oil which acts as the damper against the armature, and so damps the motion. Since the construction of this form of pickup is more complicated than that of the rubber-damped type, it is more expensive.

544. Volume control: The output voltage at the terminals of the pickup can be controlled smoothly by means of a potentiometer of about 50,000 ohms resistance connected across it. The two ends of the full resistance are connected across the pick-up coil. The output terminals connect between the arm and one end of the potentiometer, as shown at (B), (C), and (D) of Fig. 410. In this way, any fraction of the total voltage generated in the coil may be made available at the terminals of the pickup and applied to the input terminals of the audio amplifier. Most pickups are constructed with the volume control potentiometer built into the base.

545. Scratch filter: Due to the fact that the sides of the wavy grooves in a phonograph record are not cut absolutely clean and smooth, little microscopic rough edges are present. These affect the motion of the needle as they go past it, and are responsible for the generation of audio-frequency voltages of around 4,500 cycles. These are reproduced by the loud-speaker as "scratchy" sounds. This is commonly called "needle scratch". These voltages can be effectively by-passed by means of a series wave trap tuned to about this frequency, and connected directly across the pickup coil. An inductance of about 200 millihenries connected in series with a fixed condenser of .004 to .006 mfd. will be in resonance at the scratch frequency and will effectively suppress it. This forms a *scratch filter*.

Most of the better pickups are so designed as to eliminate most of the scratch. Others have a suitable scratch filter built into them. Scratchy sounds coming directly from the record and needle, due to the rubbing or scraping effect of the needle on the record, will be found to come direct from the phonograph cabinet, and can be stopped by closing the cover each time the phonograph is played. While the electrical method of playing phonograph records will work with the older form of records, the reproduction is not as good as when the new Orthophonic type (electrically cut) records are used. In former years, records were made mechanically by a machine which had many defects, and their frequency-range was very limited. Thus, many of the musical instruments in an orchestra were never heard at all, because they were not recorded on the record. Now the records are cut by an electrical recorder which has a wider frequency-range, and produces records which are far superior, both in accuracy in cutting of the groove, and wider frequency-response limits. Practically the entire useful frequency-range of musical instruments is recorded, and all of the instruments in the orchestra are heard (see Art. 9).

545A. Connection to radio receiver: If the phonograph pick-up is to be used with the radio receiver in the home, it can be connected in several ways, as shown in Fig. 410, provided it is of the high-impedance type.

At (A), a double circuit phone jack is wired into the detector plate circuit of the receiver, as shown. The pickup is plugged into this jack and feeds into the primary of the 1st a-f transformer in the receiver. A more common method, which enables the pickup to be connected permanently to the receiver, is shown at (B). One side is permanently connected to the B+ side of the a-f transformer. A single-pole

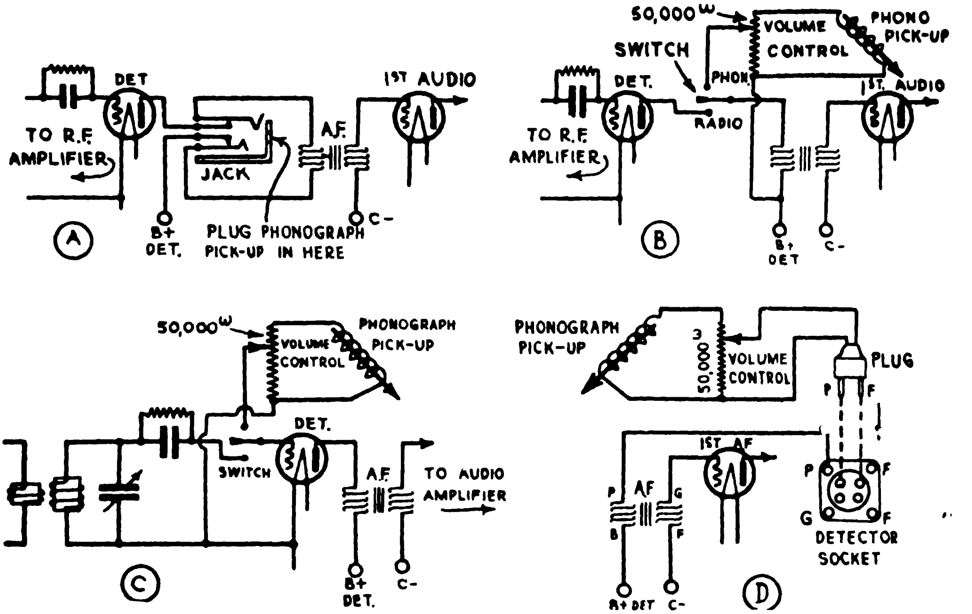


Fig 410—Various circuit arrangements which may be employed for feeding the output voltage of a phonograph pickup to the audio amplifier of a radio receiver for amplification

double-throw switch, which may be mounted on the front panel of the receiver or on the tuning dial, enables the top terminal of the transformer to be connected either to the plate of the detector tube in the receiver for radio reception, or to the phonograph pickup for phonograph music. At (C), the pickup is connected to the input of the detector tube by the switch as shown. As the grid leak and condenser are put out of the circuit, the detector tube acts as an amplifier when the pickup is connected in. Thus the additional amplification of the detector tube is made use of in this connection. This method of connection is used extensively in receivers which employ only one stage of audio amplification, since the additional amplification of the detector tube (which now operates as an amplifier) helps to increase the volume. When it is applied in the circuit of a grid-bias detector tube, a slightly different arrangement must be employed. The pickup may be switched in series with the by-pass condenser which is normally across the detector grid-bias resistor. This puts the pickup and the by-pass condenser in series, and the combination is *across* the grid bias resistor. The varying voltage output of the pickup is therefore impressed across the resistor and so causes the grid potential of the tube to vary correspondingly. At the same time, a suitable resistor must be introduced across the detector grid-bias resistor, so as to reduce the grid bias voltage and cause the tube to operate on the "straight" portion of its characteristic curve instead of over the lower "bend" (detector condition).

Some pickup units are provided with an adapter for plugging into the detector tube socket. This adapter has the P and F pins connected

to the pickup, and when it is plugged into the detector tube socket, the pickup becomes connected to the input of the audio amplifier as shown at (D). For a-c electric receivers, the pickup connects between the "plate" (P) and "cathode" (C) terminals.

546. High-impedance and low-impedance pickups: When the connecting wires from the phonograph pickup unit to the amplifier are fairly short, the pickup is usually made of the high-impedance type. In this type, the coil contains several thousand turns of wire, and the pickup may have a d-c resistance of about 2,000 ohms, and an impedance something like 20,000 ohms at 5,000 cycles. A pickup of this kind delivers a rather high output voltage, (1 to 5 volts or more), and since its impedance is fairly high, it may be connected directly to the grid circuit of an amplifier tube without any impedance-matching transformer in between. This is known as the *"high-impedance"* type of pickup.

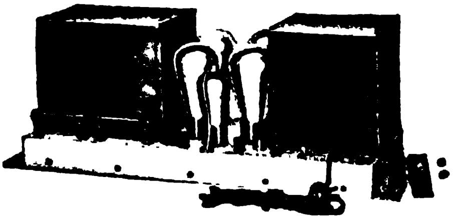
Where the pickup is located some distance from the amplifier or is to be connected to it by long wiring, the distributed capacity of the leads may be appreciable, and acts as a by-pass condenser across the pickup coil. The effect is the same as if a condenser is deliberately connected across the pickup. The higher-frequency audio voltages are materially by-passed, and the high-note reproduction suffers. This trouble may be overcome by constructing the pickup with a low-impedance coil, having fewer turns. Although this does not eliminate the self-capacity of the long extension wires, it removes the undesirable effect of it, since the proportion of the *impedance* of this shunting capacity to that of the pickup coil is now greater, and so proportionately less shunting results. Since the *low-impedance* pickups have less turns of wire on their coils, their voltage output is much less than from the high-impedance type.

Where long leads are used, it may also be desirable to employ a low impedance pickup, to avoid feed-back and the picking up of line noises. It is standard practice in theater and public address system to use either 200 ohm or 500 ohm lines, the latter being more common. When a low-impedance pickup is to be connected to the amplifier by such a line, for proper energy transfer, its impedance must be matched to that of the line by a suitable impedance-adjusting transformer. For instance, a low-impedance pickup wound to 100 ohms should be connected to a 500 ohm line through an impedance-adjusting transformer having an impedance-ratio of 100 ohms primary to 500 ohms secondary. The turns-ratio of such a transformer is equal to the square root of the impedance-ratio required (see Art. 445).

Since the net result of connecting a low-impedance pickup to the grid circuit of the first tube in the amplifier, through a proper impedance-matching transformer, is that a voltage step-up is obtained in the transformer, the disadvantage of the low output voltage is partly overcome.

547. Sound amplifier systems: Sound amplifier systems are used primarily for the amplification and reproduction on a large scale, of programs picked up, (1) directly from microphones, (2) by radio, or (3) from phonograph or film records; and many installations provide for all three. Sound amplifier systems do not amplify sound waves directly. They amplify the varying audio signal voltages applied to them, which are converted into sound waves by the loud speakers. The system may be designed to reproduce the sound in a single place, such as a large auditorium, an athletic or aviation field, a stadium, etc., or it may be used to supply the sound program to many individual places, such as the individual rooms in a large hotel, apartment house, etc. While it is obviously impossible in a book of this character, to present a detailed study of all the

various types and arrangements of commercial sound amplifier systems which may be employed, some idea of the typical apparatus which is used in this work will be considered here. Since an ordinary radio tuner and



Courtesy Electrad Inc

Fig 411 — A typical 2-stage direct-coupled audio amplifier with an output capacity of 10 watts and a 60 DB gain Its circuit arrangement is shown in Fig 412

detector system must also be used if radio programs are also to be received, the sound amplifier apparatus proper consists of audio amplifier equipment capable of high amplification and large power output, proper loud speaker equipment, and proper input, output and control circuits.

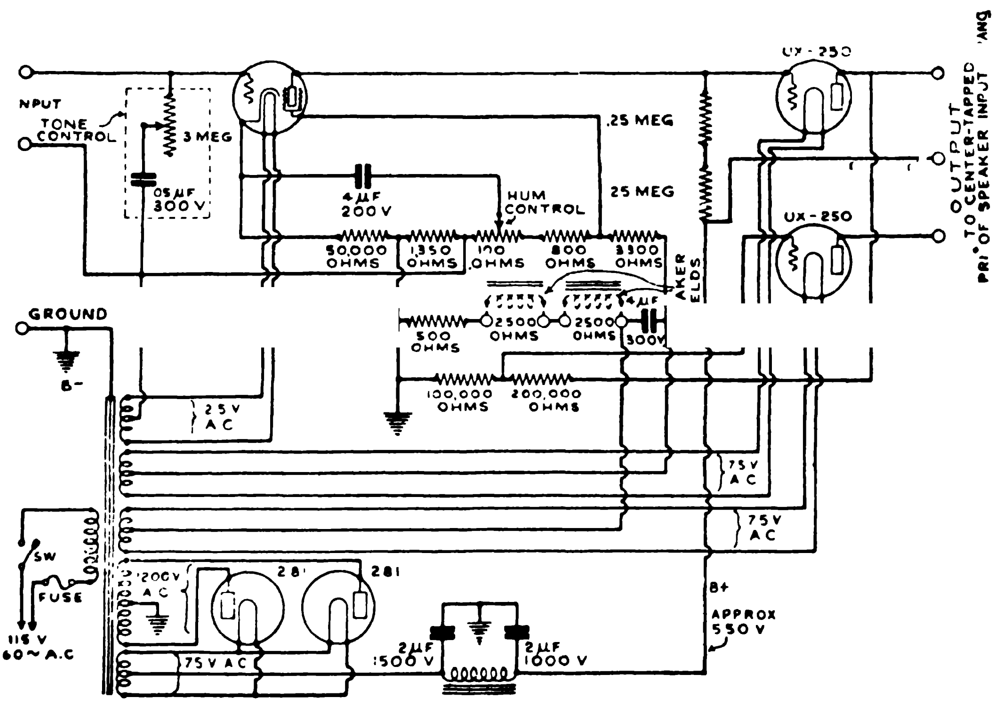
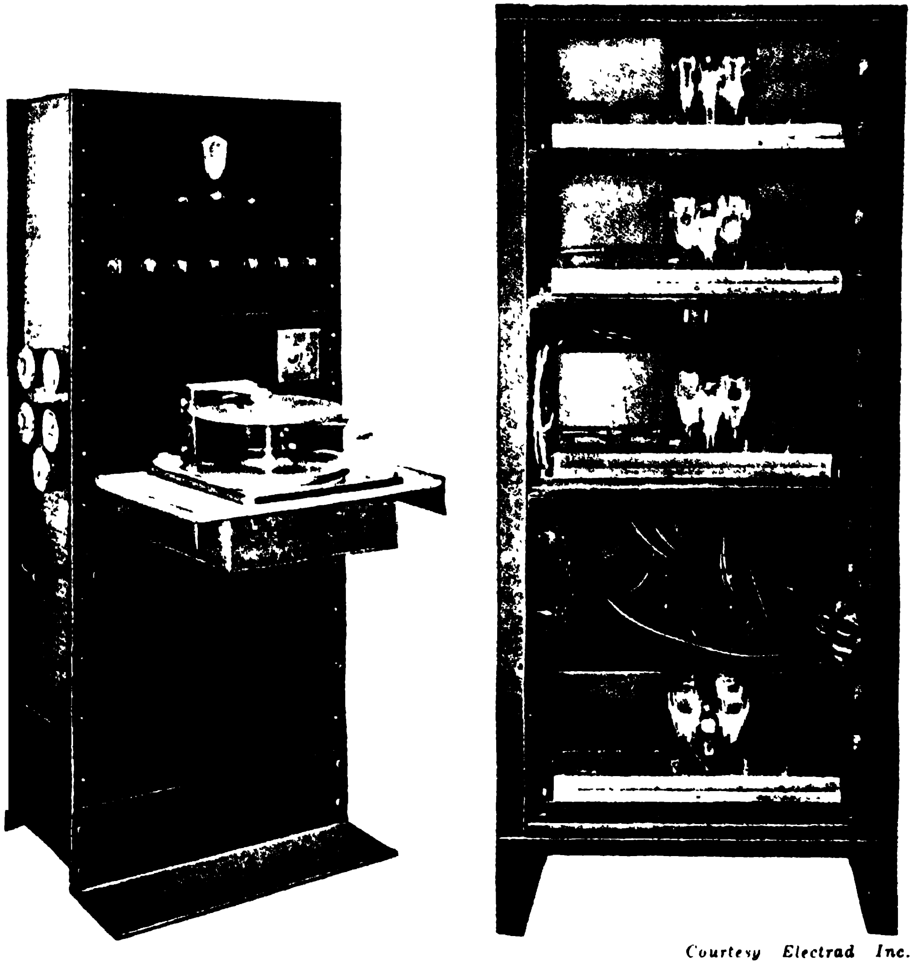


Fig. 412—The circuit diagram of the amplifier shown in Fig 411. A '24 type screen grid stage is direct-coupled to a '50 type push-pull stage, (see Art 440).

548. The amplifier: The audio amplifiers used in sound amplifier systems range from small, 2-stage audio amplifiers employing power output tubes of medium power handling capacity, to large 3 or 4-stage amplifiers constructed in switchboard fashion on racks and panels and

capable of handling outputs of several hundred watts. The power output capacity of the amplifier employed, depends upon the number and the power input requirements of the loud speakers used, which in turn



Courtesy Electrad Inc.

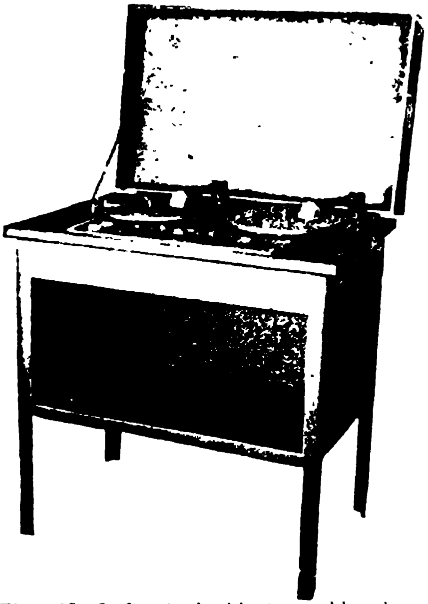
Fig 413—Left Front view of a 4-channel amplifier capable of outputting 10.3 watts of undistorted power to each channel Provision is made for either automatic playing of phonograph records by the automatic record changer at the front, for radio reception, and for microphone pickup of speech or music
Right: A rear view of this amplifier, showing the four separate amplifier units—one for each channel

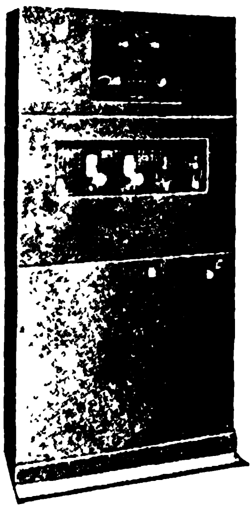
depends upon the area to be served by the system if it is used for outdoor work, or the cubical contents of the room or auditorium if it is to be used for indoor work. Since practically every installation presents different requirements in this respect, no definite figures can be given here. Specifications for the sound amplifier equipment required for any particular installation should always be obtained from the manufacturer of the equipment to be used, in order to assure satisfactory results.

For auditoriums of medium size, or outdoor work over a limited area, two-stage amplifiers of the typical form shown in Fig. 411 are common. This is a two-stage direct-coupled amplifier of the Loftin-White type, (see Art. 440).

The circuit diagram is shown in Fig. 412. It will be seen that two stages of amplification are employed, a '24 type screen grid tube in the first stage feeding to two '50 type tubes in push pull. Two half-wave rectifier tubes connected in a full-wave rectifier circuit are employed. A tone control is included at the input. This particular amplifier produces a gain of 60DB, and with an input voltage of 0.3 volts produces its maximum undistorted output of apparently 10 watts. This particular amplifier can be used with either a phonograph pickup, microphone, or radio tuner connected to its input through a suitable transformer and switching arrangement.

A typical *rack-and-panel* type amplifier unit designed to supply four different programs at one time by means of four separate output circuits





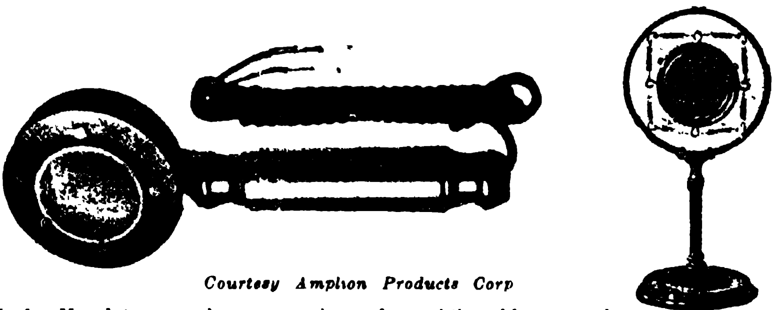
Courtesy Amplion Products Corp

Fig. 415—Left A double-turntable phonograph cabinet for a sound amplifier system used in skating rinks, dance halls, hotels, etc
Right A 50-watt amplifier for a large sound amplifier system Note the rack-and-panel construction

or *channels* is shown in Fig. 413. This can be used for high-power reproduction of radio programs, phonograph music or microphone pickup of music and voice. In rack-and-panel construction, the amplifier system is divided into interchangeable units mounted on separate metal panels which are fastened to a sturdy channel-iron frame. This saves floor space since the panels are mounted vertically, results in a rigid construction, and offers great flexibility because amplifier systems of any desired arrangement and power can be built up from standard amplifier and control units and may be added to at any time. The view showing the automatic record changer and phonograph pickup is at the left.

The top panel contains a three-stage screen-grid tuner and detector whose output can be applied to any one or all of the four audio amplifiers, and thus feed to any of the four channels. Below this is the mixer panel containing the knobs for controlling pickup, individual channel output volume, and microphone volume. It is possible to use the radio, phonograph pickup, or microphone independently, or to mix them all, by simply operating a single switch. Thus, a speaker may have a musical background to color his speech, if desired. The automatic record changer which changes 10 records and provides 50 minutes of record reproduction, is shown together with the phonograph pickup unit on the projecting shelf at the front. A rear view of this amplifier is shown at the right. A separate amplifier unit is provided for each channel supplied.

Another high power sound amplifier system with a separate double-turntable phonograph cabinet is shown in Fig. 415. The amplifier shown at the right, has a power output of 50 watts and amplifies over an audio range of 60 to 10,000 cycles with a 65 DB gain. The control knobs are shown on the top panel, with the tubes beneath. Amplifiers of this large output capacity are used for dance halls, skating rinks, stadiums, etc. Either radio reproduction, phonograph music, or microphone pickup of



Courtesy Amplion Products Corp

Fig. 416—Left: Hand-type carbon microphone for public address work. Right: Desk-type carbon microphone. Notice the spring mounting for the microphone at the center.

speech or music may be supplied. A large rack-and-panel amplifier used in sound picture work in theatres is shown in Fig. 492.

549. Microphones: Microphones used for public address work are usually of the carbon type, although condenser-type microphones are sometimes employed for high-quality pickup. The construction and operation of the carbon-type microphone has already been discussed in connection with the radio broadcasting station equipment in Article 235. A cross-section view of a carbon microphone is shown in Fig. 169.

Fig. 416 shows two typical forms of carbon microphones used in public address work. That at the left is designed to be held in the hand of the speaker, that at the right is a desk type. The microphone may also be mounted on a tall stand of adjustable height, so it reaches the level of the speaker's mouth. In general, the microphones used for speech only are constructed with a higher sensitivity but smaller frequency range than those intended to cover the complete range of speech and music frequencies. The microphone unit is suspended by springs to take up shocks and vibrations.

The battery current sent through this type of microphone should never be allowed to exceed the value specified by the manufacturer.

The construction and assembly of the various parts of a condenser-type microphone or "transmitter" is shown in the cross-section view of Fig. 417.

It consists essentially of a thin duraluminum diaphragm under tension, separated by a very small distance from a plane metal plate, the plate and the diaphragm forming the two plates of a condenser, from which the microphone derives its name. The thickness of the diaphragm is of the order of .001 inch, and the spacing between the diaphragm and the back plate is about the same distance. For broadcast purposes, the diaphragm is usually stretched to a natural vibration frequency of 8,000 cycles per second to avoid resonance effects in the a-f range normally transmitted. In use, the condenser microphone is normally "polarized" by having 180 volts connected across it, as shown in the connection diagram of Fig. 418. Sound waves striking the diaphragm cause it to vibrate very slightly. This changes the distance between it and the back plate, which changes the capacitance, causing a tiny flow of charging current to flow back and forth around from one plate through the circuit to the other. This current must flow through the 20 megohm resistor, thus setting up a varying voltage across it. This varying voltage whose wave-form is the same as that of the sound waves, is applied to the grid circuit of an amplifying tube, the same as in any ordinary resistance-coupled amplifier.

Since the capacitance of the condenser transmitter is very small, the capacity between the leads from it to the grid of the first amplifying tube must also be kept

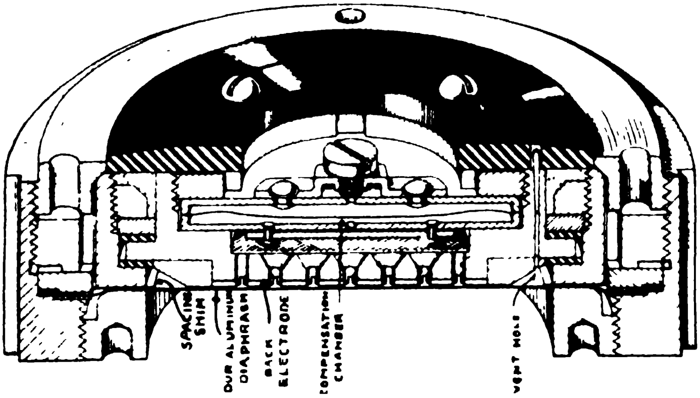


Fig. 417 — Cross-section view of a condenser-type microphone, showing the back plate and the diaphragm The sound waves striking the diaphragm cause it to vibrate, thus varying the distance and capacitance between it and the back plate

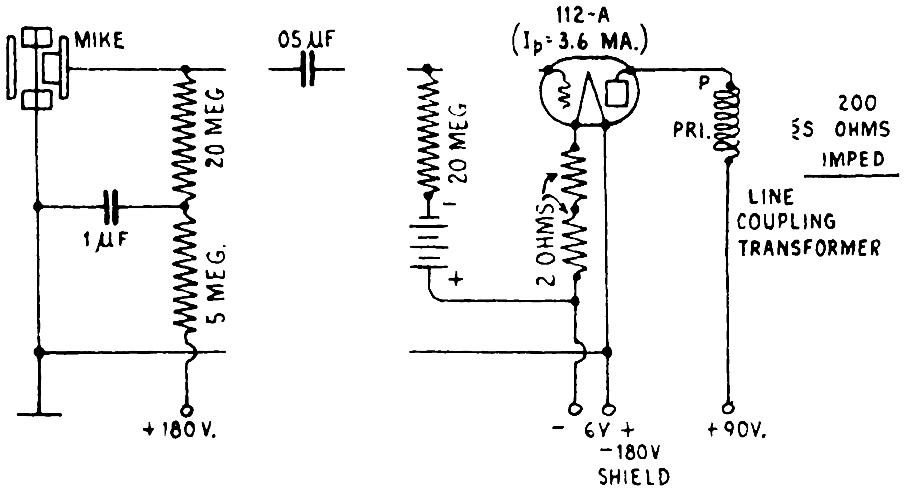
Courtesy Radio Engineering Magazine

very small or it will represent an appreciable percentage of the total capacitance of the circuit. It is general practice, therefore, to build the microphone and the first stage or two of amplification as a unit. This keeps the leads very short. A typical amplifier stage for use with a condenser transmitter is shown in Fig. 418. A line-coupling transformer for coupling this to a 200-ohm line is included in the output. The amplifier unit is built in with the microphone

The signal available from the condenser microphone is very small, so little, in fact, that two stages of amplification are usually required to bring the signal level up to that which would be produced by a carbon-grain microphone. However, absence of the usual hiss that is so objectionable in the carbon type of microphone, much better frequency characteristics, and ruggedness make the condenser "mike" the preferable of the two types where undistorted output is essential.

550. Mixing panel: Since the sound amplifier systems are commonly designed to amplify the output of either a radio signal tuner and detector, phonograph pickup, or microphone, provision must be made at the input circuit of the amplifier, to quickly throw over from one to the other and to control the input voltage smoothly. This is the function of the *mixer circuit*. While mixer circuits may be very complicated if sev-

eral microphones and phonograph pickups are to be employed, the simple system shown in Fig. 419 will serve to illustrate the general principles which are involved in them in most cases.



Courtesy Jenkins and Adair Inc

Fig 418—The circuit arrangement of an amplifier stage built in with the condenser microphone to boost its output before being fed to the line between it and the regular amplifier

Assuming that a double-button carbon microphone is to be used, it is coupled to the input of the amplifier by the impedance-adjusting transformer T_1: If the microphone has the usual resistance of 100 ohms per button, (200 ohms total), the transformer may have a primary to secondary impedance ratio of 200 to 500,000 ohms,

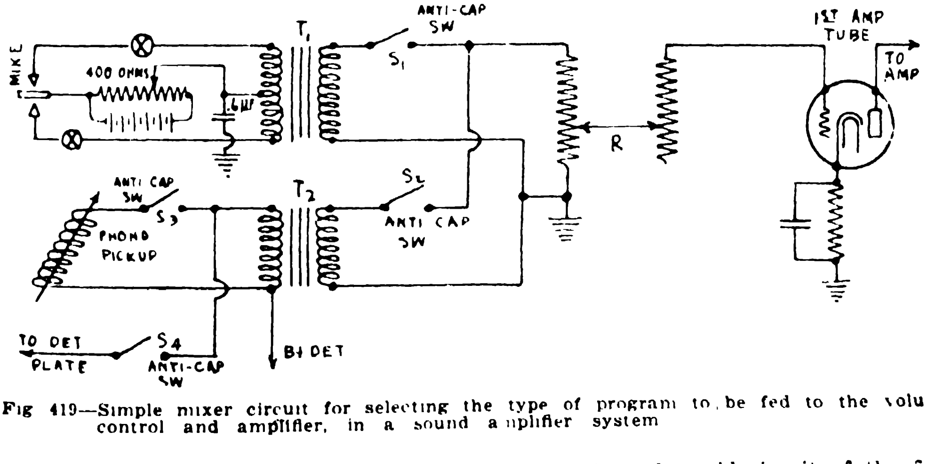


Fig 419—Simple mixer circuit for selecting the type of program to be fed to the volume control and amplifier, in a sound amplifier system

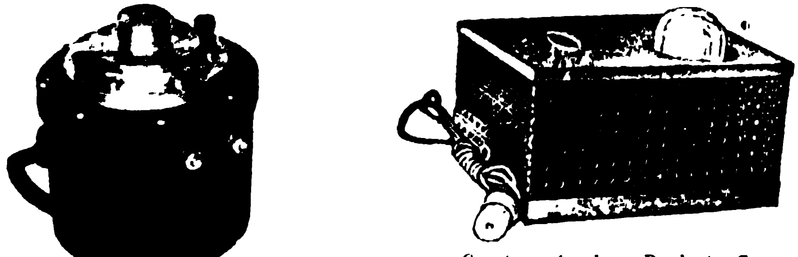
the latter being about the proper value for feeding into the grid circuit of the first amplifier tube. Four dry cells in series provide the current for the microphone circuit the current being regulated by the 400 ohm potentiometer. Jacks are provided at points X—X for plugging in a milliameter to check the microphone current. The secondary of T, may be connected at will to the grid circuit of the first amplifier tube through an anti-capacity type switch S_1. If a high-impedance type phonograph

pickup unit is employed, it may feed into the primary of the first a-f transformer T_2) and the input from the radio tuner may also feed to this, either one being connected by means of the switches S_3 and S_4. The secondary of the transformer also feeds to the tube input through a switch S_2. The volume control resistor R is common to both circuits. This is of the constant-impedance type (500,000 ohms in this case), which consists of two tapped variable resistors mounted on a common shaft and connected as shown, so that the resistance looking from either direction at R is always the same, while the signal voltage allowed to act on the grid of the amplifier tube can be varied from zero to maximum by moving the arm upwards. In this way either radio, microphone or phonograph pickup signal voltages may be fed to the amplifier at will and the volume controlled in each case. The various switches can be combined in the form of a multi-section switch for easy manipulation, and other refinements and additions may be made for more elaborate systems.

Where the amplifier is located some distance away from the pickups, additional impedance-adjusting transformers are required.

551. The loud speakers: For large outdoor or indoor installations, loud speakers of the general types shown in Figs. 353, 355, 356, and 495 are used. In many cases where the speakers are to be distributed over a large area, the permanent magnet type driving unit is employed because no field current and field supply wiring are then required—making the installation simpler and cheaper.

Electro-dynamic units for horn speakers may be of the type shown at the left of Fig. 420. The direct field current for a unit of this type may be supplied by a



Courtesy Amplion Products Corp

Fig. 420—Left: Typical electro-dynamic driving unit for an air-column type loud speaker. Right: An exciter unit for supplying low-voltage direct current for the field of the speaker unit at the left. The exciter operates from the 110 volt a-c line and contains a suitable transformer and rectifier bulb.

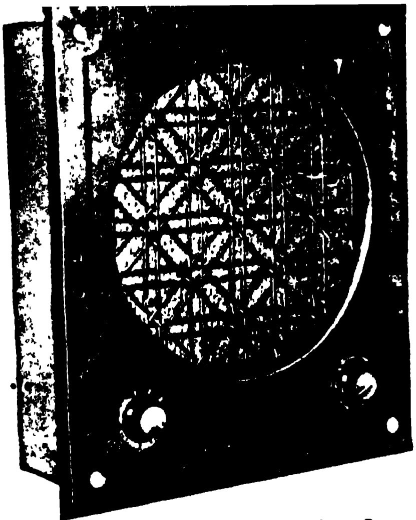
separate exciter units such as that shown at the right, operating from the nearby a-c electric light circuit. This contains a suitable transformer and rectifier, supplying d-c to the speaker field. For individual room installations in hotels, schools, apartment houses, etc., either a permanent magnet reed-type or a moving-coil type loud speaker having a cone type diaphragm, is usually built into a box in the wall of each room, with a decorative grille at the front. A speaker of this kind inside its enclosing box, is shown at the left of Fig. 421. Program channel selection and volume control is provided at the speaker itself, or at a control plate conveniently mounted on the wall.

Various circuit combinations of speakers are employed in large systems. In all cases, proper impedance-matching transformers (Art. 445) must be used when necessary. Some manufacturers provide the power stages in their amplifiers with output transformers having several taps to enable matching of the impedance values of different types or combinations of loud speakers. Thus, where dynamic and magnetic speakers operate from the same amplifier, they can be connected to different taps so that each type will be operating under the best conditions. Magnetic speakers require about ¼ watt for operation at maximum volume but only about one-twentieth watt for hotel

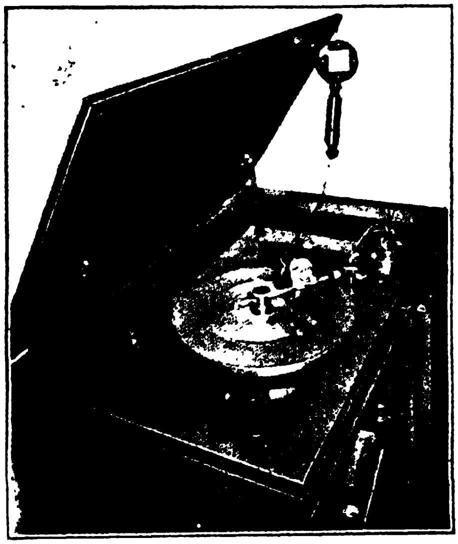
room volume. Ordinary electro-dynamic speakers require from 1 to 3 watts each for full-room volume, depending on make and type. Headphones, of course, require very low power—around 1/200 watt each. The large auditorium-type dynamic speakers handle much more power.

The wiring of sound amplifier systems assumes great importance particularly where the circuits are extensive, as in hotel, school and similar systems. The practices of installation men and also the recommendations of equipment manufacturers vary considerably as to the wiring specifications and requirements for sound amplifier installations.

No. 18 wire is probably the most commonly used size. In some installations it takes the form of twisted pairs, in others telephone cable is used, and in still others



Courtesy Best Mfg. Co.



Courtesy Presto Corp. of America

Fig 421—Left A magnetic type speaker in a wall for apartment house and home installation. Volume control and program selector knobs are provided at the bottom. A decorative grille is shown in front of the speaker
Right A home recording installation in a phono-radio combination The phono-pick-up is at the left; the recorder is at the center, and the microphone is suspended from the cabinet cover. This type cuts its own groove into the surface of a smooth aluminum disc

the wiring system is made up of shielded pairs, each pair being sheathed in a metallic wrapping to eliminate any possibility of cross-talk where the wiring of two or more channels is carried in the same conduit.

The use of standard rigid conduit to safeguard the wiring is to be strongly recommended, since this type of conduit provides against all possible forms of physical injury to the wiring. Another is the complete electro-magnetic shielding provided, preventing the pick-up of hum or other interference from neighboring electrical circuits. The third and an especially important reason for the use of rigid conduit in sound amplifier installations is that it provides the only type of wireway from which the wiring may be withdrawn for circuit alterations or into which additional wires may be drawn at any time without damage to the plaster. Thus, if additional channels are later added the new wires may easily be drawn into the same conduit with the old ones which are already installed.

552. Home recording: Home recording of speech or music on special aluminum-alloy or celluloid phonograph records makes possible

the recording of special radio programs, historic events, etc., in the home, at any time. After the recording is made, the ordinary phonograph pick-up, with a special fibre needle, is used to play back the recording through the audio amplifier and loud speaker of the ordinary home radio receiver.

There are two systems of home recording in use. In one, pre-grooved record blanks are used, the grooves guiding the cutter stylus during the recording. Either the output signal from the radio receiver, or the voice signal picked up by a special microphone and fed through the audio amplifier of the receiver, is used to actuate the cutter, while the disc is revolving on the rotating phonograph turntable.

In the other system, smooth metal discs are used. In this, the recording equipment includes a special feed mechanism operated by the turntable which feeds the cutter of the recording head toward the center of the disc as the recording proceeds. In this way the cutter cuts its own spiral groove and also records the program by means of wiggles or waves formed in the groove. Fig. 421 shows the equipment for this type of home recording installed in the phonograph compartment of a phonograph—radio combination. The recording cutter is actuated by power from the output of the audio amplifier in the radio receiver. At the left is the ordinary phonograph-pickup unit used for playing the home recorded records. At the center of the turntable is the recording head mounted in place on the feed mechanism. The hand type carbon microphone, which feeds into the audio amplifier, for speech recording, is suspended from the cabinet top. While the quality of reproduction from recordings of this kind is not comparable with that from ordinary phonograph records, home recording has entertainment value and practical worth for permanently recording programs of sentimental or historic nature, etc.

REVIEW QUESTIONS

1. Describe the process of reproduction of sound from a phonograph record of the lateral-cut type.
2. A note of 1000 cycles is recorded on a phonograph record with the turntable running at 70 r.p.m. What will be the frequency of the sound produced when the record is played back, if it is run at, (a) 80 r.p.m.; (b) 60 r.p.m.?
3. Explain, (with diagram), the construction and operation of the iron-reed type phonograph pickup. What is the purpose of the permanent magnet? In your estimation, from the point of view of lightness and small magnet dimensions for a given field strength, which would be preferable for the magnet, (a) tungsten steel; (b) cobalt steel?
4. How will wobbling of the turntable affect the reproduction from a phonograph pickup? Explain!
5. How do the low-impedance and high-impedance types of phonograph pickups differ in construction? What are the relative advantages of each type? What is the purpose of the impedance-adjusting transformer used with the former type?
6. What form of power supply is preferable for sound amplifier systems? Why?
7. Mention two important features of push pull amplification that recommend it for use in sound amplification systems?
8. What is the difference between the requirements of the audio amplifier used in an ordinary radio receiver, and those of an

amplifier used for a large sound amplifier system? How are the special requirements of the latter satisfied?

9. What is meant by rack-and-panel amplifier construction? Why is it used?
10. What is the purpose of the "mixer" circuit in a sound amplifier system?
11. A particular sound amplifier system is to be used for radio reproduction, and for phonograph reproduction from a pickup having an output of 1 volt. The power output required from the amplifier is about 5 watts. Draw a complete circuit diagram for the a-c electrically operated amplifier, with proper input circuit for either radio or phonograph reproduction, and to operate two electro-dynamic speakers with their 10-ohm voice-coils in parallel across the secondary of the output transformer. What must be the impedance-ratio of the windings on this transformer? Now add to your diagram an input circuit for a two-button carbon microphone.
12. Explain the construction and operation of the condenser-type microphone and its associated amplifier stage. Why is this amplifier stage necessary?
13. The total a-c plate resistance of the output tubes of a power amplifier is 4000 ohms. This is to be coupled to a 200 ohm distribution line, at the far end of which are to be connected six loud speakers, three of which are magnetic speakers having an impedance of 3000 ohms each and three of which are of the electro-dynamic type having an impedance of 30 ohms each. They are to be connected in two separate groups, with three of each kind in parallel in each group. Each group is fed from a separate secondary winding on the impedance-adjusting transformer. Draw the circuit diagram for this condition, and determine the impedance-ratios and turn-ratios of the windings on the two impedance-adjusting transformers required.
14. What is the essential function of the equipment used in a sound amplifier system?
15. Explain briefly the circuit arrangements and the principles involved, in home recording of sound or radio programs on both the pre-grooved type, and blank type discs. What equipment is necessary for each method?

CHAPTER 31

SHORT WAVE RECEPTION

SHORT WAVE COMMUNICATION — AMATEUR TRANSMISSION — TYPES OF SHORT WAVE RECEIVERS — SHORT WAVE TUNER SYSTEM — PLUG-IN COILS AND SWITCHING SYSTEMS — SHORT WAVE TUNER DESIGN — BAND SPREADING COILS — SIMPLE REGENERATIVE RECEIVER — FRINGE HOWL — DEAD SPOTS IN TUNING — WAVEBAND-SWITCHING SYSTEMS — SHORT WAVE SUPERHETERODYNE — SHORT WAVE CONVERTERS — SHORT WAVE ADAPTERS — OPERATING THE SHORT WAVE RECEIVER — TIME DIFFERENCES — FADING AND SKIPPING — MICRO, OR QUASI-OPTICAL RAYS — REVIEW QUESTIONS.

553. Short wave communication: While reception of programs from those radio stations which operate with carrier frequencies within the ordinary broadcast band of approximately 545 kc (550 meters) to 1,500 kc (200 meters), is perhaps most common to the average layman, a great deal of amateur, commercial, and general broadcasting transmission is also carried on by transmitting stations employing very high carrier frequencies, producing what are popularly known as *short wave* radiations. Remembering from our previous work, that the relation between wavelength and frequency for radio radiations is

$$\text{Wavelength (meters)} = \frac{300{,}000{,}000}{\text{frequency in cycles per second}}$$

it can be seen that the higher is the frequency, the lower or shorter is the wavelength. *Short* waves mean *high* frequencies. Short wave communication is therefore carried on with carrier currents, voltages, and radiations of very high frequency. Thus, a wavelength of 500 meters corresponds to a frequency of about 600 kc; a wavelength of 10 meters corresponds to a frequency of about 30,000 kc. A chart which gives the wavelengths corresponding to the various frequencies, and vice-versa, will be found in Appendix K at the rear of this book. This is very handy, as it saves the time usually required for calculations by the above formula. In general, all communication with carrier frequencies above 1,500 kc (wavelengths below 200 meters) is classed as *short wave communication.* This band is shown at the right, in the chart of Fig. 163, which should be studied carefully at this point. The general short wave band is divided up for convenience into smaller bands in which communication of particular classifications is carried on.

While ordinary short wave communication is carried on with wavelengths down to perhaps 10 meters or so, experimental transmitting and

receiving apparatus is being developed to produce radiations of higher and higher frequencies. At the present time considerable experimental work is being carried on with frequencies which are so high that the radiations produced have wavelengths as short as 18 cm. (7 inches), and possess many of the properties of light, since they are somewhat of the same character. These are called "micro-waves" or "quasi-optical" radiations, and may be reflected by ordinary reflectors just as in the case of light rays. They promise to open up a new field in radio communication. We will consider these in greater detail in Art. 570. We will confine our studies for the present, to apparatus and circuits used for ordinary short wave communication with radiations having wavelengths between about 5 and 200 meters.

Contrary to popular opinion, short wave transmission and reception, which is becoming so widespread, is not a new discovery. Owners of amateur radio transmitting stations have been communicating regularly with radiations of short wavelengths for some years Many of the leading broadcasting stations operating regularly on the broadcast band, also transmit their programs simultaneously by short wave transmission. These short wave transmissions have been heard almost all over the world, far beyond the range obtainable with the regular broadcast band transmission. As a matter of fact, high-frequency radiations are characterized by an uncanny carrying power. Low-power stations transmitting at high carrier frequencies transmit over distances that could be spanned by the lower frequencies (higher wavelengths) only by an expenditure of hundreds of times as much power. Reports of reception, on one or three tube receivers, of short wave stations thousands of miles away, has so fired the imagination and interest of many people that short wave reception of both code and phone signals has become very popular.

554. Amateur transmission: The thousands of privately-owned amateur stations throughout the world have done much to increase our store of knowledge concerning short wave transmission and reception. Owners of moderately equipped stations in widely scattered parts of the world have become neighbors and exchange almost daily conversations with their friends. The extremely low power used in most cases, makes these achievements seem almost incredible to those familiar only with the large broadcasting stations operating on the regular broadcast wavelengths, with as much as 50,000 watts of power.

Several important advantages of short wave communication are, the fact that even long-range short wave communication can be accomplished with comparatively small amounts of power; that short-wave communication is fairly free from "static"; and that the short wave band covers such a large range of frequency making it possible to assign wavebands to thousands of stations, without danger of interference. Signals from short wave stations employing but a few watts of power have been heard thousands of miles away, whereas our large broadcast band stations may use 50,000 or more watts of power and be received within a radius of only a few hundred miles. The large frequency band in the short wave range is very important. In the ordinary broadcast band between 200 and say, 550 meters, (a range of 350 meters), there is only a frequency range of approximately 1,000 kc. In the short wave band between 5 and 200 meters (a range of only 195 meters) there is a frequency range of 59,000 kc. Obviously, many more transmitting stations can be accommodated when such a large frequency range is available, assuming that each station takes up a frequency band or channel 10 kc wide. This is one of the reasons why television broadcasting is carried on in the short wave range, as we shall see later.

555. Types of short wave receivers: Short wave receivers must perform exactly the same tuning, amplifying and de-modulating functions as do the ordinary broadcast band receivers which we have already studied,

so it is natural to find that the general circuit arrangements employed in short wave receivers are the same as those used in the broadcast band types. Very simple short wave receivers usually consist of a regenerative detector with or without one or two stages of transformer-coupled a-f amplification. Next we have the receivers employing a stage or two of tuned screen grid r-f amplification. The more elaborate receivers are of the superheterodyne type. These have come into popular favor on account of their greater sensitivity, due to the fact that considerable amplification may be more readily obtained at the low intermediate-frequency existing in the i-f amplifier than can be conveniently obtained when amplifying the incoming high-frequency signal directly.

In general, the tuner circuit and construction in a short wave receiver, is possibly the only part of the receiver system which differs radically from that of the ordinary broadcast band receiver. We might possibly say that the detector also differs somewhat, since detectors of the sensitive grid leak-condenser type are commonly employed, in the simpler receivers, usually with regeneration. The audio amplifier systems are practically identical with those of broadcast-band receivers.

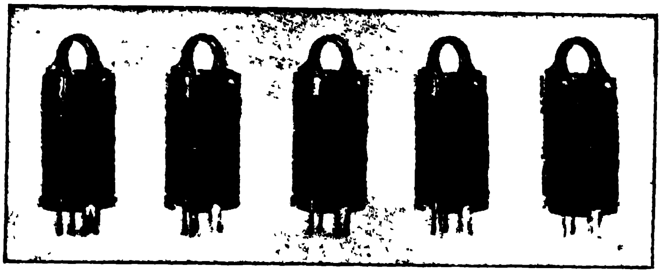
In designing and constructing short wave equipment, many problems are encountered, which are not met with in dealing with equipment designed for reception of signals at the lower carrier frequencies (higher wavelengths). Due to the high frequency of the signal voltages and currents existing in the circuits, the layout of all parts and wiring must be given much thought, as inductance and capacity effects between wires and between coils, etc., are very important. All wires from grids and plates of tubes should be kept short and well separated. Unless care is exercised in wiring the variable condensers, troublesome hand capacity effects are liable to result. This makes tuning very difficult, and is manifested by a change in the tuning of the set whenever the hand is brought near the tuning dial. The wire from the grid of the tube to the tuning coil and condenser should always be connected to the *stator* plates of the tuning condenser, and the frame and *rotor* plates should go to the grid-return circuit and ground. Complex circuits using multi-stage amplifiers are usually either unstable, or have too many operating controls, to be of value. As the tuner design in short wave receivers is a special problem we will consider it first.

556. Short wave tuner system: The purpose of the tuner in any radio receiving system, is to allow the varying signal voltages of the one station it is desired to receive, to get through and act on the grid circuits of the amplifier tubes, and to offer a high opposition to the signal voltages and currents which have been induced in the antenna circuit by the radiations of all other stations—thus suppressing them so they are not heard. Furthermore, the tuner must be adjustable, so that it may permit the reception of the modulated carrier-signals of any of many stations, within the frequency range for which the receiver is designed to operate.

In most broadcast receivers, the matter of tuner design is comparatively simple. Experience has shown that a single inductance coil of proper value, associated with its single variable tuning condenser of about .00035 mf. maximum capacitance will form a resonant or tuned circuit, which, by varying the capacitance of the tuning condenser, may be adjusted to resonance to incoming signals of any frequency within the broadcast band range of say 200 to 600 meters (1,500 to 500 kc). Thus, a single tuning condenser and coil in each tuned stage will easily cover the tuning range of 1,500 minus 500, or 1,000 kc required. The broadcast receiver usually has a dial with 100 divisions to cover the 180 degree movement of the rotary plates of the tuning condenser. If the tuning dial is moved through 100 dial divisions and if the condenser

and coil arrangement is such as to give say, absolute straight-frequency tuning over the entire dial, then it would be possible to tune in 100 different broadcasting stations, one at each division of the dial, each with a separation of 10 kc, providing the receiver were sensitive enough to receive this many stations and it were selective to 10 kc. We find therefore, that our broadcast band receivers use a single tuning coil and a single condenser in each tuning circuit, to cover the entire broadcast band of frequencies.

The tuning problem in short wave receivers is not nearly so simple. If we consider the required tuning range of the receiver to be from 10 to 200 meters, we find that this corresponds to a frequency range from about 30,000 to 1,500 kc, or 28,500 kc—just 28.5 times as large as the tuning circuits in our broadcast receiver must cover. This is because each change of one meter in wavelength at the low wavelength ranges, is caused by a much greater frequency change than a change of one meter



Courtesy Pilot Radio & Tube Corp

17 to 30 •Meters	30 to 52 Meters	45 to 105 Meters	93 to 203 Meters	200 to 500 Meters

Fig 422—A set of 4 plug-in type tuning coils for use in a short wave receiver. The waveband which each coil covers with a .00016 mf. tuning condenser is marked under the coil. Notice that the coils have been purposely designed so that the wavebands overlap somewhat

wavelength in the upper ranges. This may be seen graphically in the Wavelength—Frequency Channel Chart in Appendix J at the rear of this book.

This means, that if a short wave receiver were designed to cover this entire short wave band with a single tuning coil and condenser in each tuned circuit, they would have to cover a tuning range of 28,500 kc. If the dial had 100 divisions, each division would represent 285 kc. If transmitting stations are assigned frequencies 10 kc apart, 28 different stations might be tuned in and out by a movement of one division of the dial. Obviously, such crowded tuning is absolutely impractical. Even if this crowded tuning were practical, the system itself would be impossible to design with any degree of efficiency, since no simple tuning circuit with a fixed coil and a variable tuning condenser can be made to cover a frequency range of anywhere near 28,500 kc. The tuning condenser adds some capacity to the circuit even when it is set with its rotor plates all unmeshed from the stator plates. In addition to this, the distributed capacity of the tuning coil winding, and stray capacities existing in the circuit tend to tune the coil even when the tuning condenser is set at its zero dial setting. Therefore while a particular coil and condenser might be designed to tune to the lower frequency of the band satisfactorily, they would never tune to the higher frequency, or vice versa.

557. Plug-in coils and waveband-switching systems: This problem has been solved in two ways in practice. One method is to construct the receiver either with several easily-removable tuning coils or condensers, or both. In the latter case the coils or condensers can be changed for each of the many narrow wavebands into which short wave transmission is now divided. In this way, each coil-condenser combination is required to tune

over only a reasonable frequency-band. These are, the 160 meter, 80 meter, 40 meter and 20 meter amateur bands and the broadcast short-wave bands at 50, 25 and 20 meters. While the short wave band is considered to extend to 200 meters, there is very little communication of interest on wavelengths between 150 and 200 meters.

Many short-wave sets have been built with a non-removable variable tuning condenser, and a number of removable plug-in coils, which are wound for tuning to the various wavebands. Fig. 422 shows a typical set of these plug-in coils used in a popular short-wave receiver. The coils with the larger secondary windings are for tuning to the higher wavelengths, (lower frequencies). In this way, each coil is used for tuning only to a narrow range of frequencies and the tuning is not so crowded on the dial. The tuning coils for short wave receivers are mostly of the simple solenoid type. For the high frequencies, only a small inductance is required, and comparatively few turns of wire are necessary. The turns are usually spaced from each other to reduce the distributed capacitance of the winding. These coils must be wound accurately, as the change in inductance caused by one turn more or less of wire will cause quite some difference in the tuning range of the coil-tuning condenser combination. Some special receivers are built with removable plug-in variable condensers of various sizes.

The more common method now is to use a switching arrangement for switching in additional inductance sections for tuning to each successive band of higher wavelength (see Art. 563). While such switching arrangements are often rather complicated, they simplify the operation of the receiver, since it is merely necessary to turn the "waveband selector" knob in order to select the proper tuning inductance for tuning in the particular waveband desired, instead of opening up the receiver cabinet and inserting different plug-in coils. A typical receiver employing such a switching system will be described in Art. 563.

558. Short wave tuner design: When the tuning condenser plug-in coil arrangement is used, it is necessary to employ tuning condensers of lower maximum capacitance than is common for broadcast band reception, in order to be able to tune down to the low wavelengths around 15 meters.

Ordinary 0.00035 mfd. condensers have a *minimum* capacity which is too high to enable the set to get down to 15 meters if a practical coil with any turns at all is to be used with it. Tuning condensers having a smaller maximum capacity employ less plates and therefore their minimum capacity (plates all un-meshed) is very much lower. Consequently they are always used in short-wave receivers. A common short-wave set tuning condenser size is about 0.00016 mfd. maximum capacity. This usually has a total of about 8 or 10 plates. While the arrangement of plug-in tuning coils or a switching arrangement, solves the problem of covering all of the wave bands, each coil having a slight overlap over the next smaller size so that there will be no "holes" in the wave-band covered, there is set up one disadvantage which, is quite serious. This disadvantage has to do with the crowding of the dial for a particular wave-band. Let us suppose that for the 40- and 80-meter bands ample spread of the tuning response is obtained over the tuning dial. Yet when the 20-meter coils are plugged into the coil sockets the whole band might be bunched together within a few divisions of the dial. To overcome this evident crowding on the 20-meter band, we may resort to the expedient of removing plates from the tuning condenser, but this procedure has a detrimental effect on the tuning for other wave-bands.

This problem may be solved by the use of *special band-spread coils.* Coils of this type are plugged in in the same manner as the standard

coils and without making any changes in the receiver itself. The result, in the case of the 20- and 40-meter amateur bands, is a 50-division spread, located right in the center of the dial.

Unfortunately it is impossible to spread the tuning out on the dial and still have the same frequency-range completely covered by a given number of coils. If it is desired to cover the same range but have the tuning opened up it can only be done by using a larger number of coils and lower tuning capacity or something else which will be the equivalent. However, it may be that the owner of a short-wave receiver is interested only in certain portions of the band between 20 meters and 200 meters. An amateur, for instance, may be interested only in the American amateur bands. All he wants is to cover a narrow band at 20 meters, another at 40 meters and another at 80 meters. The wavelengths in between hold little interest for him.

The use of old vacuum tube bases as forms on which to wind short wave plug-in tuner coils has become very popular since these bases already contain the plug-in prongs and a suitable Bakelite form for winding. The primary and secondary winding on coils of this type may be arranged as shown in Fig. 422A. The ends of the coils are soldered to the tips of the hollow brass prongs. A time-saving design chart for short wave coils wound on vacuum tube base forms is shown in Fig. 422A. This is published here by courtesy of Mr. George Crammer, its originator. The instructions for using this chart are reprinted herewith by courtesy of Q. S. T. Magazine in which they originally appeared.

"Perhaps the most common case is that of determining the proper number of turns of a given size of wire to obtain a desirable tuning range in the receiver, when used with a tuning condenser of given capacity range. The first step is that of determining the capacity range of the circuit. The minimum and maximum capacity of the tuning condenser should be known and to these values should be added the "dead" capacity of the other parts of the circuit which parallel the coil and condenser. These comprise the capacity of the tube and coil base and socket, grid-to-filament capacity of the tube, capacity of the wiring, etc. If the antenna is coupled through a small capacity, this will cause a further increase. It is extremely difficult to assign a value for this capacity but in most cases it will probably fall somewhere between 20 and 40 mmf., although it is perfectly possible to have values differing from these."

"A straight edge should be run from the point on Scale VII corresponding to the capacity of the circuit with the tuning condenser at maximum, through the point on scale VI corresponding to the lowest frequency desired in the range of that coil. The point at which it crosses scale V will give the required inductance. Holding this inductance value, the straight-edge can be shifted along scale VII to the condenser's "minimum" capacity value to check the highest frequency to which the circuit will tune. If the range is too large, the tuning capacity may be reduced or additional fixed capacity employed; the former is preferable. If the range is sufficient, the value of inductance can be varied to put the desired frequency range in the center of the capacity range which will give more margin as regards the difference between the actual and the guessed-at value of 'dead' capacity."

"In order to determine the number of turns of wire necessary to give the desired inductance, the number of turns of wire per inch should be known. For a tight winding, this may be obtained from the table in Fig. 288. By lining up on the one-inch point on scale, I-II with the size wire and type of insulation as given on scale II, the straight-edge will indicate the number of turns per inch on scale I, (Fig. 422A)."

"The last step is to find the number of turns to give the required inductance and give the proper length of winding. This value has been reached when the straight-edge connects the inductance value on scale V with the number of turns on scale IV which will just take up the length of winding indicated on scale III. A few trials may be necessary to arrive at this value, but there should be no great difficulty in reaching the proper answer. After the figure has been obtained it would be advisable to check through the problem from the other end to see if the coil determined

upon will give the frequency range desired with the change in capacity permitted by the circuit."

"The above solution is predicated on the assumption that the wire will be wound with no spacing between the turns. The desired inductance may be obtained without reference to wire size by choosing any convenient length and winding in that space the number of turns indicated on scale IV by the straight-edge when placed so as to connect the proper values on scales III and V. In this case the only limitation to be observed is that a size of wire must be chosen which will allow winding the necessary number of turns in the given space. The use of scales I, II and I-II will readily check this. The wire should be wound so that the spacing between the turns is uniform."

"The formula from which the chart was constructed, assumes that the coil is in free space, a condition which is of course not realized in practice. The presence of another coil near the one under consideration, such as a tickler coil wound close to the tuning coil or an antenna coil closely coupled thereto, may result in an effective

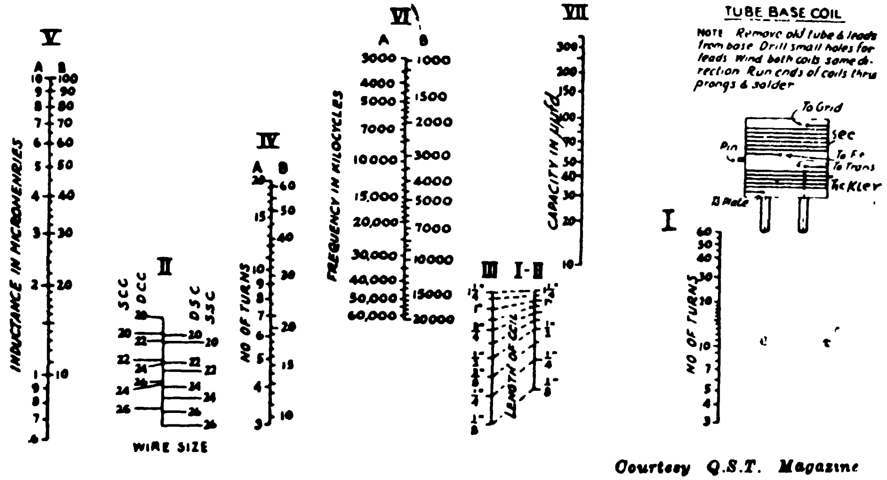


Fig. 422A—Rapid design chart for designing tube-base plug-in coils for short wave receivers.

value of inductance quite different from that which might be expected from calculation. However, if coupling between the coils is loose, or capacitive instead of inductive antenna coupling is used, the inductance of the coil will not be affected to any great extent. For many reasons a tickler coil of small diameter compared to that of the tuning coil is desirable, and it has been found that a jumble-wound coil of about ¼-inch diameter placed inside the tube base at the bottom is very satisfactory. This construction has the added advantage that the coil is easily removed for changing the number of turns if necessary, its field can be readily reversed without rewinding or changing connections, and fine adjustment of feedback may be had by bending it in relation to the tuning coil. Such a coil also has less effect on the constants of the tuning coil than one wound directly alongside it. Final adjustment of the inductance to exactly cover the bands desired is usually accomplished by adding or taking off a fraction of a turn of wire. The antenna winding usually consists of one or two turns of wire wound around the coil socket base."

559. Band-spreading coils: In cases such as mentioned above, the band-spread type of tuning coil is very useful. Instead of the entire winding of a coil being shunted by the tuning condenser, only a part of it is so shunted. The range of the coil is therefore accordingly reduced, and the tuning is opened up proportionately. In order to shift this particular desired band to the most suitable place on the dial, a trimmer condenser included in the coil is adjusted once and therefore requires no attention un-

less some further movement of the band is desired at a later date. In other words, the trimmer condenser permits the operator to select the particular portion of the band to be included within the tuning range.

One consideration involved in shunting a tuning condenser across only a part of a coil is that when the condenser is adjusted for minimum capacity, the coil is tuned close to its natural period. Unfortunately, the circuit resistance increases rapidly as

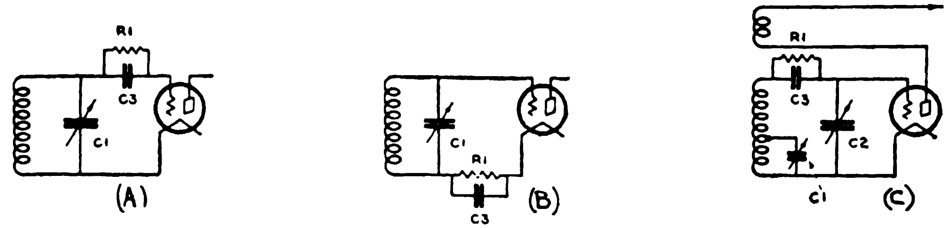
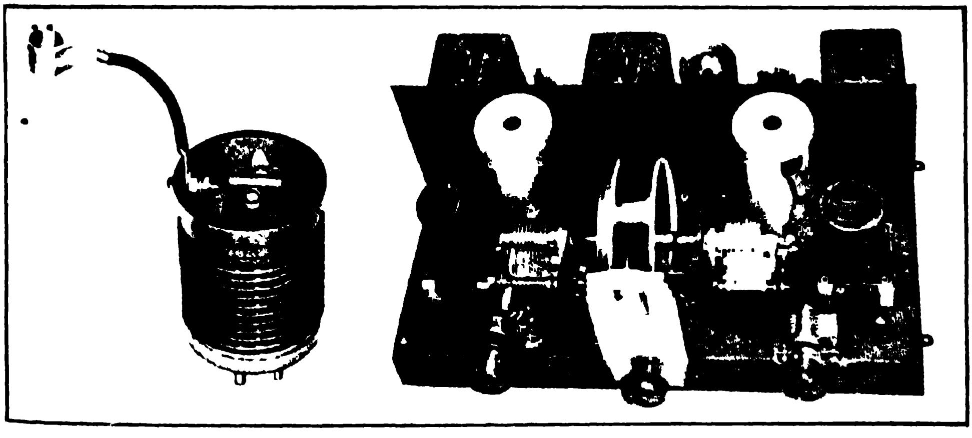


Fig 423—Band-spread coil arrangement. (Left) The conventional detector circuit with grid-leak and condenser at the top of the coil between it and the grid of the tube. (Center) Here the grid-leak is located in the grid-return to filament line, providing the same results as at the left (Right) The band-spread circuit showing the grid-leak and condenser in a new position.

the frequency approaches the natural period of the coil. But in the case of the band-spread coils the shunt capacity furnished by the trimmer condenser plus the capacity of the tube itself keeps the circuit well below the natural frequency of the coil.

Inside the band-spread type coil is a small grid leak and grid condenser as well as an adjustable low-capacity trimmer condenser. To understand the band-spread arrangement, let us refer to Fig. 423. At (A) is shown the conventional tuned circuit for a detector stage. Here, a coil is shunted by a variable tuning condenser, the top end of the coil connecting to the grid of the tube through a grid leak which is shunted



Courtesy The National Co.

Fig 424—A band-spread type s w. coil is shown at the left. Under the trimmer condenser shown at its center, are the grid-condenser and grid leak At the right is a typical s.w. receiver with the band-spread coils in place.

by a grid condenser, while the lower end of the coil is brought directly to the filament. A variation of this circuit is shown at (B) where the grid leak and condenser are connected in the grid-filament return lead. (C) shows the band-spread arrangement. C_1 the regular variable tuning condenser of about .0001 mf. now shunts only a portion of the total inductance, while the grid leak R_1, and the condenser C_3, connect directly

to the top of the coil. Finally, the trimmer condenser C_2 shunts this whole arrangement and is in parallel with the tube capacitance (about 3 mmfd). A typical plug-in coil of this type is shown at the left of Fig. 424. Notice the mica compression-type condenser inside the coil and the connection clip for the cap of the screen-grid tube. A typical short wave receiver in which these coils are used is shown at the right. This uses a stage of t-r-f amplification, regenerative detector and an audio amplifier. Single-dial control of the two tuning condensers is employed. This illustration gives a good idea of modern plug-in coil type short wave receivers arrangement and construction.

560. Simple regenerative receiver: The circuit diagram of a simple short wave receiver designed to use plug-in tuning and regeneration coils L_2 and L_1 is shown in Fig. 425. This employs 2-volt type tubes and

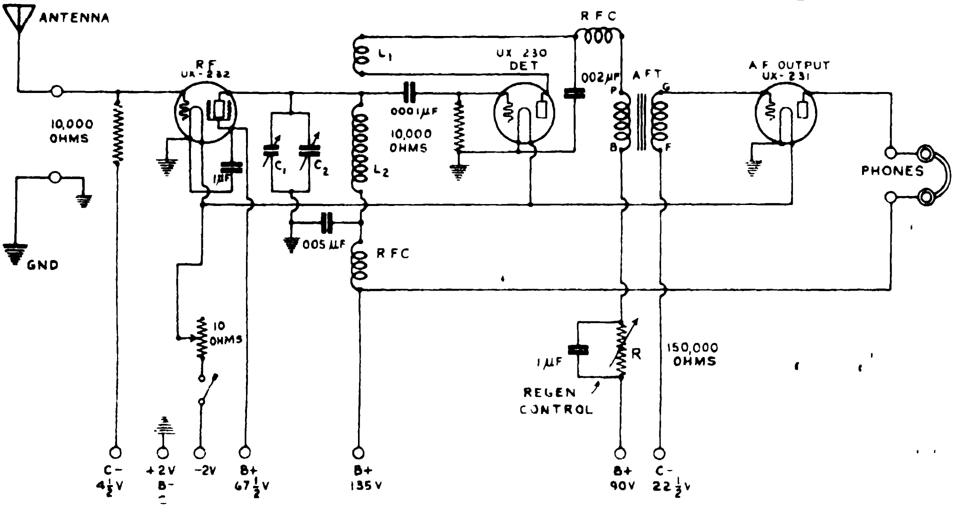


Fig. 425—A simple 3-tube regenerative s-w. receiver employing 2-volt type tubes and designed for home or portable use. Regeneration is controlled by resistor R in the detector plate circuit. For greater volume, an additional audio stage may be added. This receiver is designed for dry battery operation

is designed for battery operation for either home or portable use. For home use, an additional stage of transformer-coupled a-f amplification may be employed.

The antenna-ground circuit is completed across the 10,000 ohm resistor. The r-f variations in the signal voltage appearing across this are applied to the grid circuit of the screen grid r-f amplifier tube and are amplified by it. The coupling between the r-f and detector tubes is of the tuned-plate type. Band-shifting condenser C_1 (and a midget condenser C_2 across it for vernier tuning) tune the plug-in coil L_2. The r-f choke and .005 mf. by-pass condenser are for filtering the r-f impulses from the plate supply unit. The .0001 mf. coupling condenser and grid leak resistor complete this part of the circuit. The tickler or regeneration coil L_1 is connected in the plate circuit of the detector. Since the .002 mfd. plate circuit condenser is connected outside of this, the rectified r-f varying plate current flows through L_1, and since it is inductively coupled to L_2 with the proper phase relation, some energy is continuously being fed back from the plate circuit to the grid circuit and is therefore re-amplified by the tube. This *regeneration* results in additional amplification and so increases the loudness of the signal. The detector is followed by a single stage of transformer-coupled a-f amplification, although an additional stage may be added to produce louder signals. The amount of regeneration obtained by coil L_1 may be varied very smoothly

by means of resistor R which really controls the plate voltage and plate current, and therefore controls the amount of r-f current flowing through L_1, and therefore the feedback. Resistor R should be well constructed, since a poorly designed resistor here will cause rapid variations in the plate voltage and current which will be heard as "scratchy" noises in the earphones or loud speaker.

Simple short wave receivers of this general type are very effective, and capable of excellent reception under favorable receiving conditions. The use of regeneration in broadcast band receivers was common at one time, but fell into disrepute because in practice, it was usually pushed to the point where side-band frequency suppression or cutting resulted, and the tone quality was impaired. Regeneration has been used extensively in short wave receivers simply on account of the extra sensitivity gained by it, but as more sensitive circuits are perfected, the need for the regeneration will no longer exist, and it will probably not be used to such a great extent. There is no doubt but that regeneration is really helpful in short wave receiver operation however. It really serves two purposes; it makes the receiver more sensitive and makes it easier to find the stations, since by setting the receiver into oscillation, the various short wave transmitters can be located by the whistle produced when they are passed over. This is a great advantage where several stations may come in and out for a movement of one division of the tuning dial. Then the regeneration is backed down to stop the whistle, and the program is there. The objection to this, is that each regenerative receiver acts like a miniature transmitter when it is set into oscillation. In congested districts, this causes interference in the receivers of neighbors.

The grid leak size is important in short-wave sets. It is sometimes found that higher values of grid leak greatly control the ease with which the detector goes into oscillation, (see Arts. 331 and 333).

561. "Fringe howl:" A great many short wave receivers are troubled with a condition known as *fringe howl* or threshold oscillation, that is, when the regeneration is increased just under the point where the tube acts as an oscillator, the receiver breaks out into an audio howl. This condition is caused by radio-frequency disturbances which have found their way into the audio amplifier. It is not usually troublesome with one stage of amplification, but when two stages are used, the receiver becomes unmanageable.

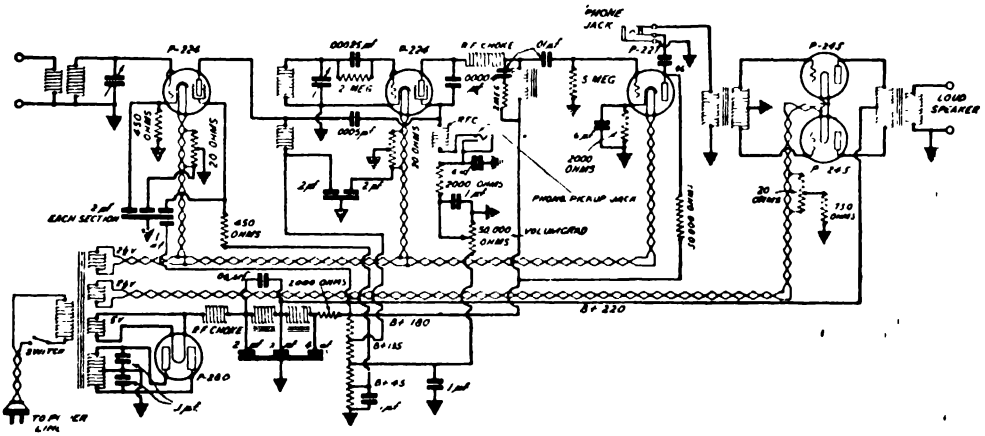
Increasing the amount of regeneration will stop it, and taking the tube completely out of oscillation will stop it, but since the most sensitive point by far is just under oscillation and since the noise is usually of an extremely annoying character, it is very desirable to remedy it if possible. One common, simple method of eliminating it is to shunt about a 100,000 ohm resistance, (commonly of the grid-leak type)—as high a resistance as possible—across the secondary of the first audio-frequency transformer If a 100,000-ohm grid leak is sufficient to stop the howls, it will be found that it does not cause any appreciable loss in amplification and the circuit seems to remain exactly as it was before the addition of the resistance, except that the "fringe howl" has stopped.

562. "Dead spots" in tuning: Many owners of short wave receivers are troubled by the fact that at certain dial settings so-called *dead spots* or narrow frequency bands exist, over which either the receiver cannot be made to regenerate at all by means of the regeneration control, or an unusually large increase in its setting is necessary. These dead spots are caused in a variety of ways, and they may also be eliminated if their cause and nature is thoroughly understood.

A "dead spot" on the tuning scale of a receiver means simply, that at the frequency corresponding to that dial setting, there exists a condition which causes the feedback to be reduced and the receiver does not oscillate properly. For the purpose of studying "dead spots", a regenerative receiver may be considered simply as an oscillator. Any oscillator can produce only limited power up to a certain point, beyond this the output drops rapidly, and finally the oscillator ceases to operate.

Any circuit tuned to resonance with an oscillator absorbs energy from it. If this absorption is too great for the power of the oscillator considered, the latter cannot operate properly. This is the reason for the "dead spots" on the dial of a short-wave receiver; there are tuned circuits which absorb power at those frequencies. One of the offending circuits, is usually the antenna circuit of the receiver. The antenna, with its coupling coil, is tuned by its total antenna-ground capacity, (see Fig. 179) to a definite frequency, determined by the values of inductance and capacity in the antenna circuit. If these values are such that the "natural frequency" is the same as that to which the regenerative receiver is tuned, the antenna circuit absorbs energy from the oscillating detector circuit, and the oscillator will "plop" out of oscillation, simply because it can no longer supply the total power required to keep it oscillating, plus that being absorbed from it by the tuned antenna circuit. Under this condition, no oscillations can be produced, ordinarily; or else a large increase in the setting of the regeneration control is necessary.

The regeneration-control, however, has a limited range, and cannot be increased



Courtesy Pilot Radio & Tube Corp.

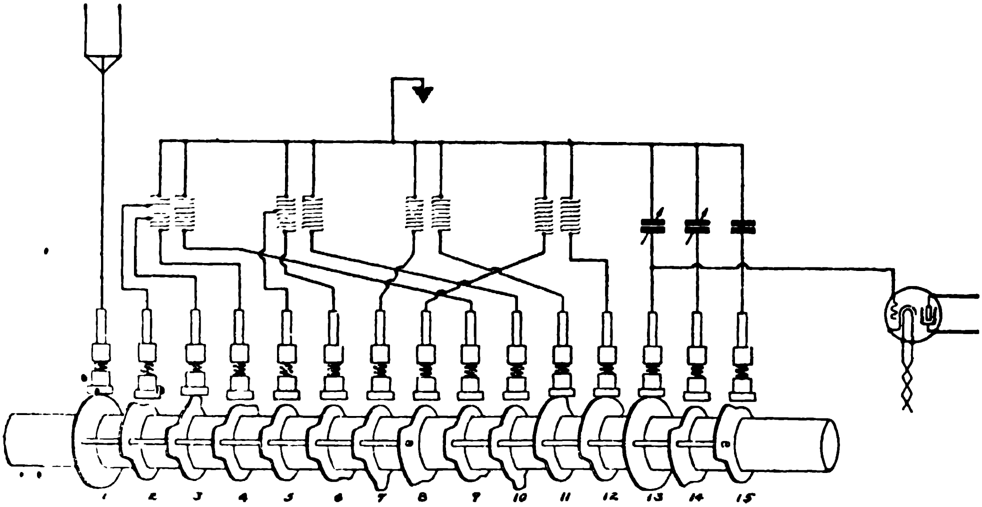
Fig. 426—This schematic circuit diagram of the Universal receiver described in Art 563 is a functional diagram and does not show the actual connections to the cam switches. (See Figs 427, 428 and 429)

very far before its entire range has been covered; so that the receiver will no longer oscillate.

The antenna system causes dead-spots also at the *harmonics* of its natural frequency; but these are less pronounced and not so disagreeable, because the regeneration control setting need be increased only slightly for these. Dead spots may also be caused by resonance in the r-f choke used in the plate circuit of the detector itself, or by apparatus near the receiver. It is possible to obtain dead spots from choke coils or tuned circuits near the receiver; and it is not necessary for a circuit to be closed upon itself in order to produce a "tuned" circuit.

Assuming that all apparatus has been removed from the immediate vicinity of the receiver, let us consider various means for removing all dead spots from the dial. Since a dead spot is caused by resonance, it will, in general, be possible to eliminate such resonance by detuning the circuit causing the trouble. It is possible not to remove a dead spot entirely, but to shift it to some frequency which is not covered by the receiver dial. In the case of dead spots caused by the antenna circuit, a variable condenser of the 23 plate midget type (.00001 mf.) connected in series with the antenna circuit will usually permit of shifting the dead spot to another frequency each time. In sets employing plug-in coils, the dead spot may reappear when a different coil is plugged into the receiver; but, if the series condenser in the antenna circuit is variable, the dead spot can again be shifted outside the new tuning range. In the case of an r-f choke causing a dead spot, turns of wire may be added to or removed from the choke to shift its natural resonance frequency and the dead spot.

563. Waveband-switching systems: While the use of the plug-in type tuning coils in short wave receivers satisfactorily solves the waveband tuning problem from the electrical point of view, it is rather inconvenient to be constantly unplugging and plugging in different coils when operating such a receiver and "fishing" for stations on the various wavebands. It is convenient to employ a coil-switching arrangement by which the proper tuning coil and condenser combination for tuning over a certain band may be selected at will by the mere twist of a selector switch or knob. While lack of space does not permit of a complete detailed de-



Courtesy Pilot Radio & Tube Corp.

Fig 427—Schematic diagram showing the switching arrangement for the four antenna coupling coils and tuning condensers. The metal cams make contact with the respective contact plungers when rotated to the proper positions.

scription of such switching devices and systems, some idea of a commercial arrangement which has been developed for this purpose may be obtained from the accompanying illustrations of the Pilot "Universal" Super Wasp receiver. The circuit diagram of the entire receiver is shown in Fig. 426.

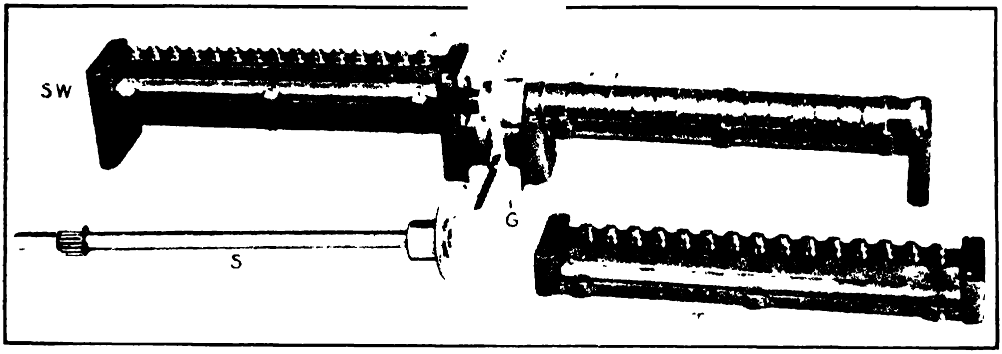
This receiver uses one stage of screen-grid t-r-f amplification, a regenerative screen-grid detector, one impedance-coupled audio stage using a '27 type tube, and a push-pull output stage using two '45s. Notice the r-f choke in the "B" power supply unit circuit, to prevent r-f disturbances originating in the '80 rectifier tube, from being transferred to the plate circuits of the receiver and causing noises in the output.

The tuning coils are fixed inside the set, and are thrown in and out of the circuit by means of a very ingenious pair of rotary cam switches encased in molded Bakelite housings, (shown in Figs. 427 and 428). This switch, which is controlled by a simple little knob on the front panel, has seven positions, and covers seven wavelength ranges as follows: (1) 15 to 23 meters; (2) 22 to 41; (3) 40 to 75; (4) 70 to 147; (5) 146 to 270; (6) 240 to 500; and (7) 470 to 650. This unusually wide wavelength range takes in not only all the short-wave channels, but also the entire broadcast band, and even the calling waves used by commercial ship and shore telegraph stations.

For the sake of simplicity, the four antenna couplers used, are represented as a single antenna coupler in the diagram, and the four detector coils are also represented

as a single coil. Each of these coils has two windings. One end of each coil is brought to a contact on the cam switches, and they are automatically connected in the proper sequence as the switches are turned.

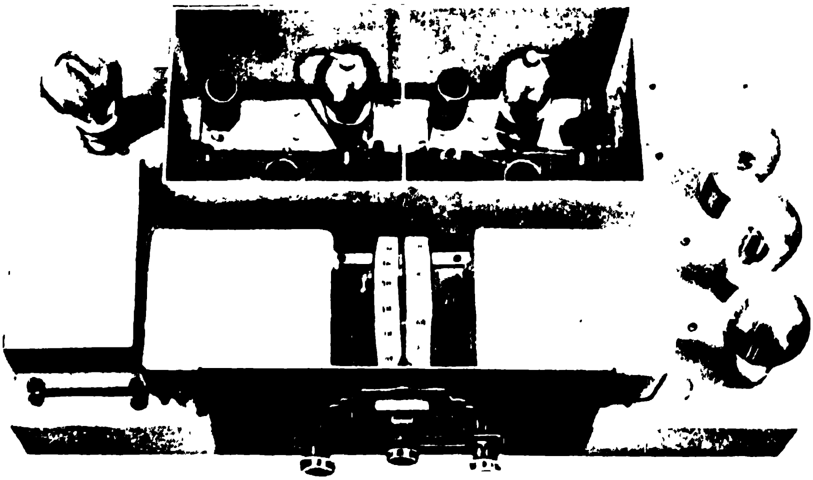
The antenna and detector tuning condensers, shown in the diagram, are actually double units; one section has a maximum capacity of 130 mmf. and the other 415 mmf. They have a common rotor connection but separate stators; the latter are also



Courtesy Pilot Radio & Tube Corp.

Fig. 428—Central switching arrangement. The switch for the antenna coupling circuit is at the left. The one at the right is for the detector circuit. (See Fig. 427.)

brought out to contacts on the cam switches, there being 15 contacts altogether on each stator, as shown in Figs. 427 and 428. At different positions of the wave-band switch, different combinations of tuning inductance and capacitance are obtained automatically by means of the cam switch, and tuning in that particular band is accomplished in the usual way by varying the setting of the variable tuning condensers.



Courtesy Pilot Radio & Tube Corp.

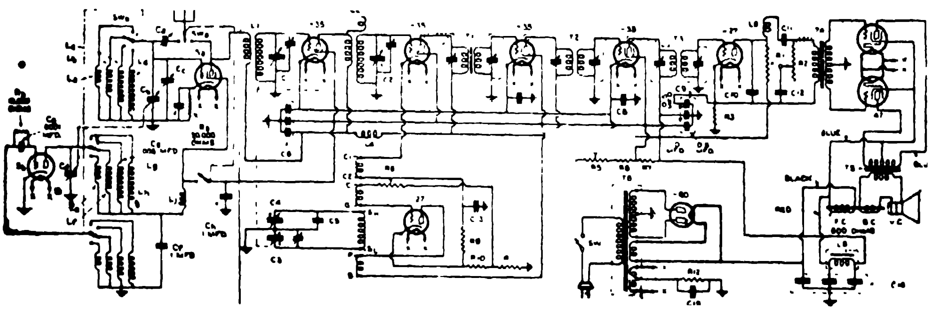
Fig. 429—The complete short wave receiver whose circuit diagram is shown in Fig. 426. The various coils are shown in the two center shield boxes.

The shift from one waveband to another is made in an instant and it is not necessary to open the receiver cabinet or disturb anything.

Fig. 427 shows a schematic view of the connections of the tuning coils and condensers, and the cam and contact plungers of the half of the rotary waveband selector cam-switch used for the antenna-coupling circuit. As the shaft is turned, the

metal cams 1-2-3-4 etc., which are insulated from each other, come around in proper order and make contact with the metal plungers above. The fixed condenser at the right is a .0004 mf. loading condenser used only to tune to the highest waveband, above 470 meters. The actual switching device is shown in Fig. 428. P is the contact plungers on the assembled switch for the antenna coupling coils. C shows the cams molded in Bakelite, for the detector coil switch. G is the worm gear drive. S is the drive shaft and T is the top piece for the detector switch. A top view of the complete receiver is shown in Fig. 429. The r-f and detector shielded compartments with the coils and tubes are at the rear center. The tuning dial and shielded tuning condensers are at the front center. The power supply unit is at the left. The wave-band selector knob is at the lower center.

The receiver circuit of Fig. 426 shows a novel regeneration system. The r-f current for the plates of both the r-f and detector tubes, and the screen grid current of the detector tube, is led back to the tickler winding through the .00004-mf. condenser between the screen grid and the plate, and C4 the .0005-mf. condenser at the lower junction of this circuit. The r-f choke coils in the plate and screen-grid leads prevent the r-f current from taking any other path. The control of regeneration is pro-



Courtesy Radio News Magazine

Fig. 430—Circuit of a typical short wave and broadcast band superheterodyne with a wavelength range of 10 to 550 meters (550 to 30,000 k c). The various wavelength ranges are selected by the selector "tap-switch" SW-6. No plug-in coils are employed

vided by a 50,000-ohm potentiometer, regulating the screen-grid voltage. This arrangement provides very smooth regeneration, the control of which does not affect the tuning circuits. Thus it is possible to log station settings very definitely.

Other waveband switching systems in which specially designed multiple "tap switches" are used to perform the coil-switching operation, are in common use and are very satisfactory, (see Fig. 430).

564. Short wave superheterodyne: The use of the superheterodyne principle (see Chap. 22), in short wave receivers, presents the practical advantage of doing the amplifying of the weak signal voltages more efficiently at the comparatively low frequency existing in the i-f amplifier, than it can be done with an equal number of amplifier stages directly at the incoming carrier frequency. The general circuit arrangement of a short wave superheterodyne receiver is practically similar to that of an ordinary broadcast band receiver, as will be seen from the circuit diagram of the Silver Marshall 726 S.W. combination short wave and broadcast band superheterodyne receiver shown in Fig. 430. Compare this for general

arrangement with the circuit of the somewhat similar type of receiver for broadcast-band reception only, which is shown in Fig. 283.

Since the conditions regarding image frequency, etc., are different in the case of short wave receivers than they are in broadcast band receivers it is common to use an intermediate frequency of around 650 kc in the receivers for short wave reception instead of the 175 kc commonly used in broadcast band receivers. For broadcast band reception, the requirements make it common to use 175 kc as the intermediate frequency. Therefore, if the receiver is to be used for both short wave and broadcast reception, both i-f's should be employed, (see Art. 386).

It is obviously not practical to build a superheterodyne receiver for both short and broadcast wavelengths with two different intermediate-frequency amplifiers, for the equipment cost would be very considerable. This problem has been nicely solved in this receiver by designing the main i-f frequency amplifier for 175 kc, this being preceded by the oscillator, first detector, and r-f tube for broadcast band reception. As soon, however, as the receiver is shifted over to operation in the range of 10 to 200 meters, a scheme popularly known as *double suping* is resorted to—the use of two intermediate frequencies with two oscillators, one fixed and one variable.

Specifically, the broadcast tuning dial is set to some clear channel in the neighborhood of 650 kc—it may actually be anywhere between 600 and 700 kc and this done, the broadcast band r-f amplifier tube and first detector together with their tuned circuits comprise the first level of intermediate-frequency amplification, which takes place obviously at the setting of the broadcast dial or at 650 kc, approximately. A short-wave first detector is then placed ahead of the r-f amplifier tube which has now become an i-f amplifier tube, and to this tube is coupled a short-wave oscillator which is arranged to track away from the short-wave first detector by approximately 650 kc in order to produce the first intermediate-frequency. At first glance, it may be a little difficult to grasp the exact operation of this arrangement, but a little consideration will undoubtedly make it clear.

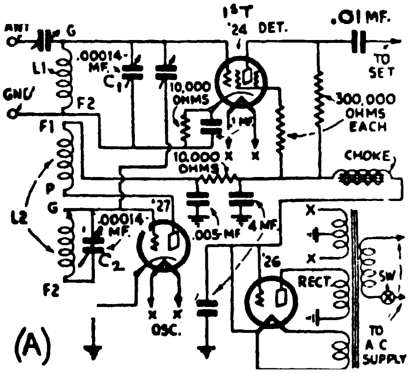
The coils for the various wavebands are easily selected by means of the four-position switch SWB, controlled by a knob. This same switch selects one of four oscillator coils, in proper order to work with the four first-detector tuning coils.

565. Short wave converters: Without doubt, the superheterodyne system is the best known system for short wave reception, inasmuch as it is the only one which permits a high order of amplification to be obtained, due to the insurmountable difficulties encountered in building high-gain short wave r-f amplifiers. While it is of course desirable to employ a superheterodyne receiver designed especially for short wave reception, it is a fact that a large proportion of radio enthusiasts already own a broadcast band receiver which may represent a considerable investment. They do not care to purchase a separate receiver for short wave reception. Where a suitable broadcast band receiver is available, it may be converted into a short wave superheterodyne receiver by means of a "short wave converter".

One often hears the terms s.w. converter and s.w. adapter used interchangeably, while actually there is quite a difference between the two. The term "converter" should be applied only to devices which convert one frequency into another frequency. A converter may be used as the first detector of a superheterodyne arrangement. A *short-wave converter* is an electrical arrangement which converts the short wave signals into corresponding long wave signals so that the short wave programs can be received on an ordinary broadcast receiver. The r-f amplifier in the broadcast receiver itself functions as the intermediate-frequency amplifier of the superheterodyne. It is usually necessary that this intermediate-frequency amplifier should give considerable amplification for good loudspeaker reception. Usually, this requires that it shall consist of radio-frequency stages employing screen-grid tubes. Short wave "adapters" will be considered later.

The *short wave converter* is really a frequency changer. It consists usually of a first detector, tunable local oscillator, and self-contained power supply unit, although in some cases it may also have a stage of t-r-f amplification ahead. The converter is connected to the antenna and ground terminals of the broadcast-band receiver. The oscillator output heterodynes with different incoming short-wave signals, resulting in a beat-note or "difference frequency" in the intermediate amplifier, which in this case consists of the tuned r-f stages of the broadcast receiver set at some fixed tuning frequency. Some converters used the filament and "B" voltages from the broadcast receiver, others use separate batteries, and still others have their own socket power supply unit. A circuit of an a-c tube electrically operated short wave converter with its own power supply unit is shown at (A) of Fig. 431.

The '27 type tube acts as the oscillator, due to the magnetic coupling between plate and grid coils L_2. The grid circuit of the oscillator is tuned by condenser C_2.



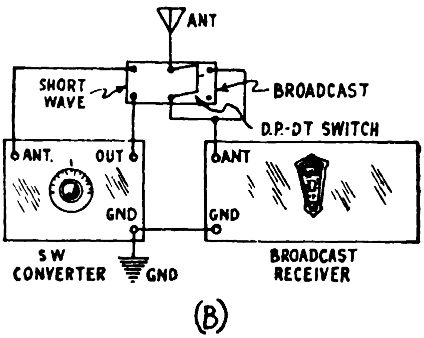


Fig. 431—Left Circuit of an a-c tube electrically-operated short-wave converter with its own power supply unit.
Right: Connection of a s w converter to an ordinary broadcast band receiver.

Two trimmer-type condensers are used, one an antenna coupling condenser for the first detector and the other an oscillator coupling condenser—both of these require a screw driver for adjustment. C_1 tunes the first detector input circuit in combination with the tuning coil L_1, which may be of the tube-base type (see Fig. 422A). The plate circuit of the detector feeds into the "ANT." terminal of the broadcast-band receiver as shown at the right of Fig. 431. The power supply unit consists of a small power transformer furnishing filament current for all the tubes, and high voltage a-c for "B" supply which is rectified by a single '26 type tube, and filtered by a single choke and two 4 mf. dry electrolytic condensers. The '26 type three electrode tube is connected as shown, since the power supply unit is called upon to deliver only a small current, and the use of a tube of this kind which is amply large and rugged, makes the use of a smaller power transformer possible.

When the converter is placed beside any standard broadcast receiver, by simply connecting the antenna to the converter, one lead from the converter to the antenna post of the receiver and one lead from the ground terminal of the receiver to the ground terminal of the converter (already grounded), as shown at (B) of Fig. 431, and the power plug is inserted in the socket, the full conversion of the broadcast receiver to a short wave superheterodyne has been accomplished. To eliminate the converter, it is only necessary to shift the antenna lead back to the broadcast receiver again, leaving the ground connection between the broadcast receiver and converter permanently made, if desired. This may be accomplished by the simple switching

arrangement shown. These connecting wires should be kept very short to prevent them from acting as antennas and picking up signals direct from broadcast-band stations. In many cases, the antenna lead from converter to set need not be disconnected, although it is desirable to do so. When this connection is made, the r-f amplifier of the broadcast receiver tuned to some clear channel in the neighborhood of 1,000 kc, serves as the i-f amplifier for the superheterodyne, the broadcast receiver detector functioning as the second detector, and the audio channel operating in the conventional manner. In this manner, the full amplification of the broadcast receiver is utilized at short waves. The tuning of the broadcast receiver is left fixed and is not varied at all when receiving short wave programs. It is only varied when broadcast-band stations are to be received.

Unless a coil-switching arrangement is used (see Art. 563), two short-wave plug-in coils are required for each frequency band to be covered, one for the oscillator and one for the first detector. For the whole short wave band of 17 to 200 meters, a total of eight coils, or four sets, are usually required. A converter may also be used successfully in connection with a number of present-day superheterodynes, resulting in a "double super" because the frequency is shifted twice, and three detectors are employed. This combination, is capable of very satisfactory results.

566. Short wave adapters: Short wave signals may also be received with an ordinary broadcast-band receiver by using a short wave adap-

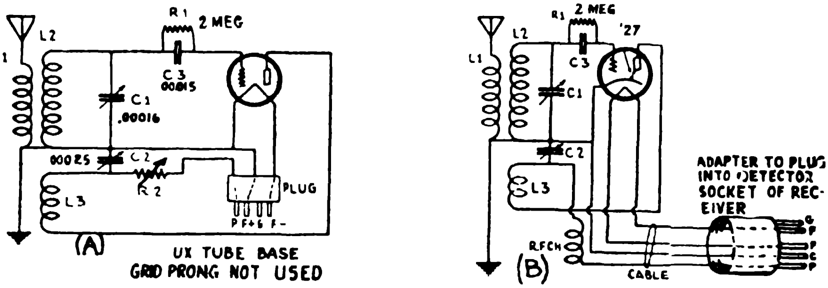


Fig. 432—(A) A short wave adapter circuit designed for use with a battery-operated broadcast band receiver
(B) A short-wave adapter for use with an a-c electric broadcast band receiver.

ter ahead. A *short wave adapter* usually is simply a short wave detector, and its tuning circuit is designed to tune to the short wave signals. No change in frequency takes place in an adapter. By means of a socket plug which is connected to the adapter, connection is made from it to the audio channel of the broadcast receiver by first removing the detector tube from the socket in the broadcast receiver, and then plugging in its place this special socket plug. In this way, the r-f amplifier and detector circuit of the broadcast receiver are cut out, and in its place is used merely the short wave detector unit which comprises the adapter. What we have then, is a simple short-wave detector circuit followed by the one or two stages of audio-frequency amplification in the broadcast receiver. In some of the older types of broadcast receivers, the radio-frequency amplification is so low that one may just as well use a s.w. adapter instead of a s.w. converter, obtaining almost equal results. If properly adjusted, an adapter gives fairly satisfactory short wave reception, and it has the advantage of having a considerably lower first cost.

Since the s.w adapter is simply a short wave detector, it is very simple to construct . A simple s.w. adapter for use with a battery-operated receiver is shown at (A) of Fig. 432. This is simply a regenerative detector employing proper short-wave plug-in tuning coils L_1, L_2, and tuning condenser C_1. The coils may be of the tube-base plug-in type designed from Fig. 422A if desired. Regeneration is obtained by tickler coil L_3 and controlled by C_2. The terminals go to a four-prong plug, which may be the base of an old vacuum tube. To use the adapter, the antenna and ground are connected to it, the detector tube in the broadcast band receiver is removed from its socket, and the 4-prong plug from the adapter is inserted in this socket instead. In this way the filament voltage from the receiver is led to the filament of the adapter tube, and the plate circuit of the adapter is completed through the plate circuit of the first audio coupling unit in the receiver. The signal output from the adapter is thereby fed to the audio amplifier and is reproduced by the loud speaker. The r-f tuner unit of the broadcast receiver is not used at all when receiving short wave signals. It is usually helpful to include variable resistor R_2 in the adaptor plate circuit to enable adjustment of the plate voltage for best regeneration control. The tube used in the adapter is usually of the same type as that used in the detector socket of the broadcast receiver. To prevent fringe howl, it may be necessary to connect a 0.1 megohm resistor across the secondary of the first a-f transformer in the receiver.

Short wave adapters used with a-c electric broadcast receivers do not always give satisfactory results, because most of these receivers use plate rectification in which plate voltages as high as 180 volts may be applied to the detector. When the adapter plug is inserted, the same plate voltage is being applied to the tube in the adapter. Also, in many a-c electric receivers, which use resistance-coupling between the detector and first a-f tube, the actual effective voltage on the plate of the detector is very low. This causes inefficient operation of the adapter detector. Since the tendency in modern receiver designs is to do most of the amplifying in the r-f amplifier and use only one audio stage, short wave adapters used with these receivers do not usually operate satisfactorily, merely because there is not enough audio amplification provided. These points are important, for in many cases, poor reception is blamed on an adapter when in reality it is due to improper operation of the receiver.

A circuit diagram for a s.w. adapter for use with an a-c electric receiver is shown at (B) of Fig. 432, but the above statements should be kept in mind regarding the undesirable operating conditions which may be forced upon such devices. It is generally more satisfactory to use a short wave *converter* with a-c electric operated receivers, unless the receiver is of such design that proper voltages are provided for an adapter. If it is desired to increase the sensitivity of a s.w. adapter, a stage of screen-grid r-f amplification can be added to it. This will give a general r-f and detector arrangement somewhat similar to those in Figs. 425 and 426.

567. Operating the short wave receiver: The knack of correctly operating short wave receivers is usually learned only after considerable experience in tuning a particular set.

Possibly the greatest trouble is caused by the fact that the novice manipulates the tuning controls much too rapidly. Due to the fact that several stations may often be tuned in and out with a movement of a division or two of the tuner dial, it should be turned *very slowly* when tuning for stations, or they will be passed right by without being heard. Short wave receivers of the regenerative type should oscillate smoothly over the entire range of the tuning condenser, with each coil. If the set is correctly designed and the batteries (or socket power device) and tubes are in good condition, the fact that usually determines whether or not the set will oscillate, is the antenna series condenser. If the antenna is too long the set will not oscillate. Instead of cutting the aerial length, a midget condenser with a capacity range of from about 0.00001 to 0.00005 mfd. may be connected in series with the aerial. Different settings

of this condenser should be tried at the various wavelengths, until the set oscillates smoothly. Antennas from 30 to 60 feet in total length, (including lead-in and ground wires), are usually suitable for short wave reception. It is important that all connections be well made and soldered. The ground connection should be made to a cold water pipe or to a separate pipe or plate buried in moist earth. The importance of good ground connections cannot be overstressed, as they are often responsible in a large measure for the good or poor results obtained with an otherwise good receiver system.

Short wave receivers of the *non-regenerative* type are tuned in exactly the same way as ordinary broadcast receivers are, only the tuning dials should be rotated more slowly. There are two methods of tuning either short wave or broadcast receivers of the regenerative type.

In tuning for short wave signals, set all controls such as the antenna series condenser, volume control, etc., at the point where loudest signals are heard on local stations. Then, throw the detector into oscillation by advancing the regeneration or volume knob *very slowly* until you hear a soft rushing sound. As you continue to turn, the noise will build up quickly in intensity and then drop off in an abrupt click. The condition of the set during the first rushing period is known as "regeneration," and in it the set is extremely sensitive. The condition just beyond regeneration is "oscillation". If you keep the set in oscillation, and turn the tuning dials slowly, you will hear a whistle when you run into a broadcasting station. With this whistle may be mixed the voice or music. The whistle or "beat note" is produced by the heterodyning of the incoming signals with the oscillations of slightly different frequency generated by the oscillating detector. To clear up the signal, simply turn back the volume knob until the set crosses the border line and slides back into regeneration.

If the incoming signal is fairly strong, the program will come through free of the whistle. However, if it is weak, the whistle will dominate the voice, as this whistle is caused by the beating or "heterodyning" of the carrier wave of the station and the oscillations generated in the detector circuit. In this case, the "zero beating" tuning method should be tried. This is always the best for weak signals, although it requires some experience in tuning.

To "*zero-beat*" an incoming signal, throw the receiver into oscillation by advancing the regeneration control, and then tune it very carefully so that the frequency of the oscillations set up by the detector are *exactly* of the same frequency as that of the incoming signals to be received. When this exact point is reached, no whistling is heard, since there is no difference in frequency, and the beat whistle disappears. The signals are likely to be somewhat distorted, but this is not usually very objectionable.

You can tell when you have zero-beated a station, by turning the tuning condenser a hair's breadth above and below the point at which the signals are understandable and clear of whistling. You will hear a whistle each time, as each time you move the condenser you change the frequency of the local receiver circuit and therefore cause a beat note to be set up which is heard as a whistle. Zero beating is an excellent means of fishing out very weak signals, because the receiver is in a very highly sensitive condition when it is oscillating. Many weak and distant stations that you cannot hear at all with the set thrown just out of oscillation you at least will be able to identify if you zero-beat them.

When attempting distant or foreign reception, the time differences between the locality of the receiver and that from which the signals originate must be taken into consideration. This will now be considered.

568. Time differences: In attempting long-distance short wave reception it is important to consider the differences in time which exist at various places on the earth's surface. For instance, it would be rather foolish for a man in New York City to listen at 8 P. M. New York time for a station in London, England which is scheduled to sign off at 12 P. M. London time. The reason for this is, that when it is 8 P. M. in New York,

it is 1 A. M. the following morning in London. Therefore that particular London Station had signed off one hour before.

Greenwich Mean Time is the system of time in which noon occurs at the moment of passage of the mean sun over the meridian of Greenwich, England. Standard time is the time of a certain meridian adopted for local use over a large region in lieu of true local time. The meridian of Greenwich, England, was taken as a prime meridian, and there are twenty-four standard meridians differing from it by 15 degrees of longitude east and west. These meridians were established in order that the standard times of all countries would agree with Greenwich in minutes and seconds but differ in hours by whole numbers. Clocks at any place within 7 degrees and 30 seconds east or west of a standard meridian are set to agree with the time of that meridian. They may therefore differ by as much as a half hour from local mean time. In the United States, the standard times are: *eastern*, 75 degrees west or five hours slower than Greenwich mean time; *central*, 90 degrees west or six hours slower than Greenwich; *mountain*, 105 degrees west or seven hours slower than Greenwich; and *Pacific*, 120 degrees or eight hours slower than Greenwich.

A chart of time differences showing the time existing at various important cities when it is 6 P. M. Eastern Standard Time in New York City is given herewith. At the right is a column giving the number of hours which the time in any city is ahead or behind that in New York City.

TIME CHART

City	Eastern Standard Time	Numbers of hours ahead of New York City
New York City	6:00 P. M.	
Chicago	5:00 P. M.	— 1 hour (behind)
Denver	4:00 P. M.	— 2 hours (behind)
San Francisco	3:00 P. M.	— 3 hours (behind)
London	11:00 P. M.	+ 5 hours
Paris	11:00 P. M.	+ 5 hours
Madrid	11:00 P. M.	+ 5 hours
Rome	Midnight following day	+ 6 hours
Petrograd	1:00 A. M.	+ 7 hours
Buenos Aires	7:00 P. M.	+ 1 hour
Bombay, India	4:00 A. M.	+10 hours
Calcutta, India	5:00 A. M.	+11 hours
Melbourne, Australia	8.30 A. M.	+14.5 hours
Sydney, Australia	9:00 A. M.	+15 hours

Thus when it is 7:00 P. M. Eastern Standard Time in New York City, it is midnight in London. (This would be 8:00 P. M. Eastern Daylight Saving Time.) A very useful time conversion chart may be obtained by sending 10 cents in American coin, to the Superintendent of Documents, Government Printing Office, Washington, D. C., for a copy of Miscellaneous Publication No. 84, entitled "Standard Time Conversion Chart."

569. Skipping and fading of short wave radiations: One of the peculiar properties of short wave, (high frequency) transmission is that the radiations may skip over certain localities and be received perfectly at points further away from the transmitter. This is known as *skipping*. Also the signals may fade in and out while being received. This is known as *fading*. The explanations of the actions which have thus far been advanced are in the form of theories. The Kenelly-Heaviside layer theory, named after its originators, is the one most commonly accepted and which seems to agree best with observed, measurable phenomena. An explanation of these actions and the basis of this theory follows:

A transmitting antenna sends out electromagnetic radiations, which, if they are not reflected or refracted, radiate out in straight lines as shown at (A) of Fig. 433. Though they are all part of the same radiations, we speak of those rays which are directed and travel near and along the earth's surface, as the ***ground rays***. Those

which are directed and travel upward, are the *sky rays*. The ground rays, following the earth's surface go through hills, forests, towns steel frameworks of buildings, etc., and are slowed down by the resistance of the path and greatly weakened, (especially at the higher frequencies) so that ordinarily the ground rays are practically non-existant at distances further than 500 miles or so, depending on the frequency. It is evident that if the ground rays alone were received by the antennas of receiving stations, long distance reception would not be possible, because of the curvature of the earth, and the rapid decrease in strength of the rays.

The sky rays do not travel in straight lines indefinitely, for if they did, they would never return to the earth, and would not affect our receiving antennas. According to the *Heaviside layer theory*, there exists all around the earth's surface, at

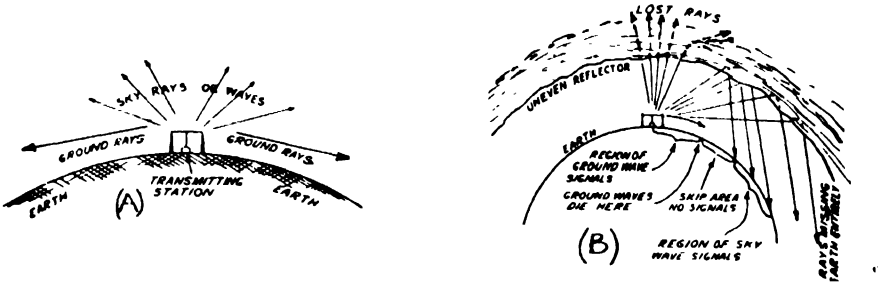


Fig 433—(A) How the radio rays from a transmitting antenna consist of those which radiate out along the earth's surface (ground rays), and those radiated up toward the sky (sky rays).

(B) The sky rays are reflected by the heaviside layer and return to the earth. They pass over, or "skip," certain places on the earth's surface entirely. Of course, the signals cannot be received or heard at these "skip-areas."

varying height of a hundred or so miles from it, an enveloping layer of ionized gas containing "free electrons." These are produced by ionization of the atoms of the gases of which the atmosphere is composed. The ionization may be caused by the action of the ultra-violet light from the sun, or from electrons shot off by the sun directly. At any rate, this layer is thought to be present around the earth. When the sky rays reach it, they are reflected from it as shown at (B), somewhat as light rays are reflected by a mirror—only the surface of the Heaviside layer is not smooth like a mirror but curved and possibly bumpy.

The action of *skipping* may now be understood. As seen from (B), the receiver may be located so far from the transmitter that it does not receive the ground rays with sufficient strength to be noticed. If the reflected sky rays return to the earth ***beyond*** the receiving antenna, no signal will be received, since these rays have skipped right over the locality in which the antenna is erected. So great is this Heaviside effect on rays such as are radiated in the 20 to 40 meter band, that the radiations skip nearby sections altogether and are received strongly at distances of 500 to 1,000 miles or more away. Hence the reflecting action which causes skipping, is also responsible for the long distance transmission possible with short wave signals, since it may return the sky rays back to the earth's surface at long distances from the transmitter. In the daytime, the strong ultra-violet rays from the sun penetrate deeper down into the atmosphere, and therefore the Heaviside layer is closer to the earth. On this account the waves are reflected almost straight down again. Hence, we are not able to accomplish much long-distance radio reception in the daytime.

At night however, the ultra-violet rays are very weak and the positive and negative ions of the air come together again. The Heaviside layer is therefore much higher above the earth. This means that the waves are reflected at a less acute angle so that they are able to spread farther out and cover a larger section of the earth. Accordingly, we are able to receive much farther at night than in the daytime.

In locations where the ground rays of a station are received together with the reflected sky rays, *fading* may be caused. In this case the signal voltage induced in the antenna at any instant is the combination of that induced by the ground rays and

that induced by the sky rays, at that instant. Remembering that these rays have come by different routes and distances, it is easy to see that they may not be in phase when they arrive at the receiving antenna. If they are in phase, they add, and the signal is strong; if they are out of phase they oppose each other, and the signal may be greatly weakened, depending on how much out of phase they are. Since the under surface of the Heaviside layer is bumpy, and is continually changing its contour, the angle of reflection of the rays changes, and they may travel longer or shorter distances before reaching the receiving antenna. Hence their phase relation with the ground rays is not constant, and consequently the amount of opposing or reinforcing taking place between the two, changes, and causes periodic strengthening and weakening of the signals, (*fading*). A station may be received strongly for a few minutes, then some change will take place in either the height or the contour of the under surface of the Heaviside layer, this changing the angle of reflection of the sky rays and therefore the distance they travel before reaching the receiving antenna. This changes the phase relation of the ground and sky rays effective at the receiving antenna. The loudness of the received signal also changes correspondingly.

Now the amount of absorption of the ground and sky rays, and the angle of reflection of the sky rays depends on their frequency. Also the angle of reflection of the sky rays, depends on their frequency. Also the earth's surface (seasonal conditions, time of day, etc.), and the condition of unevenness of its surface. Hence the fading and skipping actions are very variable, and cannot be predicted with certainty.

However, enough is known about the behavior of short wave radiations so that in practice, short wave transmitting is carried out on the particular frequencies which are most suitable for the requirements of skip and range, depending on the time of day and the distance to be transmitted. In general, for distant station reception on frequencies from 14 to 20 meters, all tuning should be done from daybreak till 3 P. M. local time. From 20 to 33 meters, stations to the east of the listener will be heard best from about 11 A. M. till 10 P. M. Stations to the west of the listener in this band should be heard best from midnight till about two hours after daybreak, when they will fade out. From 33 to 70 meters, distant stations can be heard only after darkness falls. Very little in the way of distance can be heard above 70 meters, although the ships, police, fire, coast guard and aircraft stations are all heard above that wavelength. Although these general instructions are helpful, it should be remembered that since so many varable conditions may affect the sky rays, short waves are notorious for their disobedience of the few laws that have been laid down for them. You are likely to hear stations on certain wavelengths at certain times when you should not hear them at all; also, you may "fish" for a week for stations that you heard strongly during all of the previous week, and not find a sign of them.

570. Micro, or quasi-optical rays: Ultra-short wave radio transmission by means of radiations of such high frequency that the wavelength (distance the disturbance travels during the time it takes to complete 1 cycle) is only in the neighborhood of 18 centimeters (about 7 inches) has been accomplished. These rays or radiations are called *micro*, or *quasi-optical rays*, because their wavelength is so short and they possess many of the characteristics of light rays, in that they may be reflected by ordinary reflectors such as are used for reflecting light rays, etc., (see Fig. 434).

The oscillator tube used to generate the exceedingly high frequency oscillations necessary for this type of communication system is of special interest. The tube, known as the Barkhausen-Kurz (B-K) type or *micro-radion* tube, is one in which the physical dimensions, rather than the electrical constants of the circuit attached, controls the frequency. In this tube, the filament is a straight wire, surrounded by a circular spiral coiled-grid, and outside of this, a curved cylindrical plate. The grid is

maintained positive and the plate is negative. Electrons emitted by the cathode are attracted to the grid, many of them pass through it and come within the field of the plate. Since this is negative the electrons are repelled and again come to the grid field. Thus, one oscillation takes place in the time required for an electron to make this trip, which is a very short time. Therefore, the wavelength is a function only of the size and mutual position of the electrodes within the tube, and the voltages thereon, the tube is designed in such a way that all parts which act as coupling devices are exact ratios (in size and spacing) of the desired wavelength. A shield about one inch square protects the radiating parts of the tube from the field of the antenna.

The antenna system for this ultra-short wave transmission system is very simple. In the transmission of 18 cm. rays across the English Channel from Saint Margaret's (Dover) and Calais, two double reflectors were used at each end of the system, one for transmission and one for receiving from the other side.

Fig. 434 shows the essential features of the system: The outgoing signals are applied to one of these special oscillator tubes, in which the high-frequency oscilla-

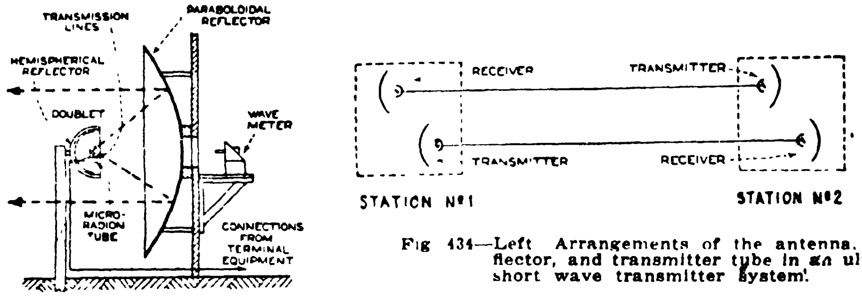


Fig 434—Left Arrangements of the antenna, reflector, and transmitter tube in an ultra-short wave transmitter system.

Right: How two radio beams can be transmitted side by side for 2-way simultaneous communication Interference between them is prevented by the narrowness of the beam, and the placement of the receiving reflector behind the transmitting reflector

tions are generated. The tube is connected to the radiating system or doublet (see Art. 231), which is about 2 cm. long, in contrast to the larger antenna systems usually employed. The amplitude of this high-frequency current along the doublet at any instant is substantially the same. The doublet is situated at the focus of a paraboloidal reflector some three meters in diameter. After concentration of the rays by the paraboloidal reflector into a fine pencil of rays, somewhat similar to light rays sent out by a searchlight, they are projected into space. In the reflector, the relation between the focal length and the diameter is so proportioned, as to insure maximum efficiency for the diameter used.

In order further to increase the efficiency of the system by the prevention of radiation other than in the required direction, a hemispherical reflector is located at the opposite side of the doublet to the paraboloidal reflector and having the doublet at its center. This serves to collect all the radiations propagated in a forward direction, and to reflect them back again towards the source. The radius of the hemispherical reflector is so chosen that when the reflected radiations reach the focus again they are in phase with those being radiated at that instant. It is estimated that the gain due to the paraboloidal reflectors on one channel is of the order of 46 decibels, to which the hemispherical reflectors add another 6 decibels.

The receiver is a counterpart of the transmitter, except that no high-frequency measuring device is provided. That is to say, it comprises a doublet connected by a line to a tube similar in construction to the oscillator tube just described, where detection takes place. Paraboloidal and spherical mirrors exactly similar to those of the transmitter, are also provided for concentrating the received rays upon this doublet. The simplicity of the system is apparent.

Since the radiations proceed in direct straight lines, they may be aimed directly toward the receiving station in a narrow beam, much as

a searchlight is aimed. Since the energy is all directed toward the receiving station in a beam and not scattered or "broadcast" as in the usual transmission system, a given distance can be covered with much less power supplied to the transmitter. It is probable that this system will find commercial application for radio beacons and navigation purposes, for secret communication etc. Since the frequency band available in the quasi-optical ray band between only 10 and 100 centimeters is about nine times as great as in the whole ordinary radio broadcast band from 200 to 600 meters, it is evident that this full band will permit the working of a very large number of transmission channels between nearby places without mutual interference or signals. Further developments are rapidly being carried on in this very interesting field of work. Quasi-optical rays are of course interrupted by any natural obstacles in their path, but, in free space they have great possibilities. Since they are directed in straight lines, they can be transmitted and received only between stations located rather closely together, due to the curvature of the earth's surface. It is possible however, to transmit messages over long distances by relaying them through a number of stations located the proper distances apart.

REVIEW QUESTIONS

1. What is generally meant by the term "short waves"?
2. What are the advantages of short wave transmission and reception? Disadvantages?
3. What is meant by "skipping" of short wave signals? Explain the reason for this action.
4. What is meant by "fading" of short wave signals? Explain its cause.
5. Explain the relation between wavelength and frequency. What is the frequency of an 18 centimeter quasi-optical radiation? (100 centimeters = 1 meter).
6. What is a waveband? What is meant by the expression that "a receiver can tune to a waveband from 10 to 200 meters"?
7. Explain why either plug-in coils or a waveband-switching arrangement must be employed in short wave receivers to cover the tuning range from 10 to 200 meters, whereas in broadcast band receivers, a single coil and condenser in each tuned circuit will cover the tuning range from 200 to 600 meters easily.
8. Why is a tuning condenser of small maximum capacity (about .00016 mf.) usually employed in each tuned circuit of a short wave receiver? Why not use a .00035 mf. condenser as we do in broadcast-band receivers, and use coils of smaller inductance?
9. Draw a circuit diagram of a battery-operated s.w. receiver having a regenerative detector and two transformer-coupled stages of a-f amplification. Plug-in coils are to be used. Explain the operation of each part of the receiver in detail.
10. Explain one method of spreading the tuning in a certain small band, over the complete 100 divisions of the tuning dial.

11. What are "dead spots" in tuning? Explain their cause in the tuning of a s.w. receiver. How would you proceed to eliminate a dead spot occurring in the tuning of a certain receiver?
12. What is the advantage of using a waveband-switching system in a s.w. receiver, instead of using plug-in coils? Has it any disadvantages?
13. Draw a circuit diagram for a superheterodyne short wave receiver and explain the action of each main part.
14. A s.w. superheterodyne is to operate with an i-f of 650 kc. What must be the frequency range of its oscillator, if signals from 20 to 200 meters are to be received?
15. What is the difference between a s.w. converter and a s.w. adapter? What are the advantages of each?
16. Draw the circuit diagram for a single tube s.w. adapter and explain its operation in detail.
17. Draw the circuit diagram for a single-dial a-c operated s.w. converter and explain its operation.
18. Describe the "zero-beat" method of tuning a regenerative receiver. Why is it called "zero-beat"? What are its advantages?
19. Explain briefly what precautions must be observed in operating a s.w. receiver as regards, (a) method of tuning in stations; (b) regeneration control, if any is used; (c) time to listen; (d) bands to listen in on at certain times of the day, etc.
20. Why are short wave receivers usually more difficult to tune than broadcast band receivers are?
21. A transmitting station in Madrid is on the air between the hours of 5 to 8 P. M., Madrid time. During what hours, Eastern Standard Time, should the owner of a s.w. receiver in New York City listen in for this transmission?
22. What are quasi-optical radiations? Why are they given this name?
23. Describe a simple beam transmitting system using quasi-optical radiations. What is the purpose of the reflectors?
24. What are the advantages of transmission in the quasi-optical frequency range?
25. What are the advantages of beam radio transmission? State two disadvantages which are important if it is to be used for radio broadcasting. How may one of these disadvantages be effectively eliminated?

CHAPTER 32

VACUUM TUBE APPLICATIONS AND PHOTOELECTRIC CELLS

HIGH VACUUM TUBES — CIRCUITS FOR MEASURING, OR WEIGHING — THE THYRATRON TUBE — THE PHOTOELECTRIC CELL — PHOTOELECTRIC CELL CONSTRUCTION — NEED FOR AN AMPLIFIER — PHOTOELECTRIC CELL AMPLIFIER CIRCUITS FOR RAPID LIGHT VARIATIONS — PHOTOELECTRIC AMPLIFIER CIRCUITS FOR INTERMITTENT RELAY OPERATION — LIGHT SOURCES FOR PHOTOELECTRIC DEVICES — SOME COMMERCIAL PHOTOELECTRIC CELL CONTROL SYSTEMS — PHOTO-VOLTAIC CELLS — RADIOVISOR BRIDGE LIGHT-SENSITIVE CELL REVIEW QUESTIONS.

571. High-vacuum tubes: While the use of 3, 4 and 5-electrode high-vacuum tubes operating on the thermionic principle is common in ordinary radio work, both these and other special forms of vacuum tubes are employed in a variety of non-radio uses. While lack of space does not permit description of all of these, a few of the more common ones will be described. New uses are being found for these tubes in industry almost every day. Vacuum tubes may be classified according to, (a) the number of electrodes; (b) the content of the bulb, which may be high vacuum, gas, or vapor; (c) nature of the fundamental electrode, the cathode, which may be thermionic, photoelectric, mercury-pool, or cold.

The ordinary forms of high-vacuum tubes which we have studied have very desirable characteristics for radio work, but they have certain serious limitations. Probably the most important of these, is the high power loss within the tube. Part of this loss is represented by the power required to heat the cathode to the point where electron emission takes place; this ranges from about 10 to 150 watts per ampere of plate current passed through the tube. Another limitation arises from the fact that since the path from the cathode to the plate has a very high resistance, from several hundred to about one thousand volts-per-ampere is required to force the current across this space within the tube.

From these facts it will be seen that plate currents of more than a few amperes cannot be handled economically by means of this type of tube. Therefore, it is apparent that in the industrial field the most promising applications of the high-vacuum tube are in various control operations where the useful factor is the unique characteristics of the tube, (such as amplifying or rectifying properties, etc.), rather than its output.

572. Circuits for measuring, or weighing: Ordinary forms of vacuum tubes are used extensively in industry for precision measurement of thickness, and for weighing. In most of these systems, the principle of the regenerative receiver using the "zero beat" tuning method is employed, (Art. 567).

An oscillator is used to supply a signal of constant frequency. A regenerative detector circuit is tuned to resonance with this by the "zero beat" method. The tuning condenser in the grid circuit of the detector controls the frequency of the oscillations generated by it. Part of this tuning condenser consists of a special 2 plate condenser, whose mechanical separation and material between the plates determines its capacitance. The condenser is constructed so the distance between these plates is the distance which is to be measured, (or the weight on one of them is the weight to be measured). Any slight change in the distance between the plates changes the capacity. This charges the frequency of oscillation of the detector, and consequently changes the frequency of the beat-note produced between it and the local oscillator. By means of a suitable indicating device in the tuned circuit, this may be indicated. The instrument is first calibrated with samples of known thickness or weight. Let us consider its application to the measurement of the thickness of paper produced in a mill. If a strip of the paper in the mill, is passing continuously between the plates of this condenser, and the circuit is adjusted to bring the tuned circuit to a point just off the resonance peak, then any variation in the capacity of this fixed condenser as a result of variation in thickness, weight, or dielectric constant of the paper, will produce a change in the capacitance which will in turn change the beat-frequency. The pointer of the indicating meter will then swing away from its central position, the direction depending on whether there is an "increase," or a "decrease," in the weight or thickness of the material of which the moving strip is made. This principle is used in paper-thickness testers, precision gauges, etc.

573. The thyratron tube: A tube designed to overcome the characteristic of large "power-loss" inside the tube, is known as the *thyratron tube.*

Its striking characteristics are the greatly decreased amount of power required to heat the cathode, and a marked reduction in the large voltage drop characteristic of the high-vacuum tube. This is brought about by the introduction of a slight amount of mercury gas or vapor into the bulb, the positively-charged vapor or gas molecules mingling with the electrons and neutralizing the space-charge This neutralization of the space-charge makes possible a very different design of hot cathode. The thyratron tube is really a development of the hot-cathode type mercury vapor rectifier and contains in addition a "control electrode." Instead of utilizing what might be termed an open-type cathode permitting the electrons to leave the hot surface easily, there may be used an enclosed-type cathode with just a few holes through which the stream of neutralized and negative ions may pass. This means that the heat may be kept within and conserved, whereas the electrons and positive ions may be allowed to travel to the anode. This is accomplished by surrounding the hot cathode with heat insulation and heat reflectors with only relatively small holes for the passage of the current. The resultant power-loss is only about one watt per ampere of current through the tube, compare this with the 10 to 150 watts-per-ampere power-loss in the high-vacuum tube.

Also, neutralization of the space-charge eliminates the high voltage necessary to pass the current through the space; and instead of a large voltage increasing with the amount of current to be carried there is a constant-voltage drop of from 10 to 20 volts.

As a result, a thyratron tube built to about the same physical size as the common UX-250 high-vacuum tube, and costing about the same amount to manufacture, will handle about 50 times as much current as the latter. It is apparent therefore, that the gaseous type of electrostatically-controlled tube is much better suited to the handling of relatively high currents common in the broad field of electrical engineering than is the controlled high-vacuum type.

Nevertheless, a thyratron tube has certain limitations; the high-vacuum type can handle currents up to a frequency of one million cycles per second, whereas the thyratron in its present form is limited to a few thousand cycles per second.

The thyratron tube may be used as a rectifier for changing large amounts of a-c current to d-c. A rectifier circuit of this type is shown at (A) of Fig. 435.

With the larger thyratrons, polyphase circuits are usually employed in order to minimize the amount of filter required for smoothing and to

attain the usual advantages of such circuits. A single-phase controlled rectifier circuit is shown.

Another fundamental application principle is the *inverter.* This changes direct current to alternating current and may be either separately-excited or self-excited, depending upon the source of power applied to the grids.

There are several types of inverters, but the general principles are similar. In every case, d-c voltage is applied to the plate of the tube and the grid is supplied with the frequency it is desired to obtain, or else from a circuit tuned to this frequency. In this respect, an inverter may also be considered as a thyratron amplifier or oscillator. The function of the tubes is to commutate, or in other words, perform a switching operation. In all inverters, some form of power storage is necessary in order to supply power during the commutation period. This may be in the form of static condensers, or a power system with leading power factor, or in rotating apparatus.

The fundamental action is simple and may be illustrated by the diagram at (B) of Fig. 435. The plates of both tubes are positive. Assume that the grid of the

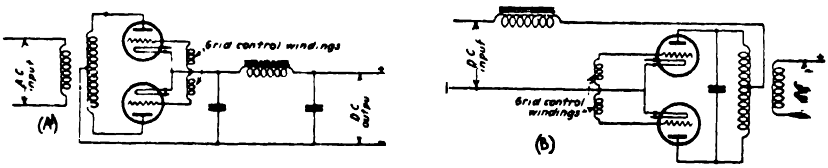


Fig 435—(A) Controlled single phase rectifier and filter circuit using two thyratrons.
(B) A single phase inverter changing d-c to a-c employing two thyratron tubes.

upper tube is positive. Current will flow from the positive d-c source, through the transformer, to the negative d-c line by way of this tube. The grid of the lower tube is negative and allows no current to pass. The condenser is charged with the potential drop across the output transformer, due to the current flow in the upper half of the winding, the upper terminal becoming negative and the lower positive. Toward the end of the cycle the grids exchange polarity. This has no direct effect on the current flow through the first tube, but allows current flow through the second, which in effect connects the lower side of the condenser to the negative lead. This places a negative voltage of short duration on the upper plate, allowing the upper grid to regain control. As this action continues, voltage is generated in the output winding. As with the controlled rectifier, the usual power applications would be polyphase. One interesting radio application of the thyratron inverter has been its use for converting 110 volts d-c into a-c, in order to make it possible to operate standard types of a-c tube electrically-operated radio receivers from 110-volt d-c lighting circuits.

It seems probable that the rectifier and inverter application of the thyratron will revolutionize the power transmission field. Long distance power transmission has been carried on mostly by means of alternating current. It is now possible to generate the electrical power at high voltage in a-c generators, step it up to very high a-c voltages with transformers, rectify it to very high-voltage d-c by thyratron rectifiers, transmit it over the lines as d-c, convert it to a-c at the end of the line, step it down to normal voltages with transformers, and distribute it in the regular way as low-voltage a-c. The advantages of a system of this type will be apparent from the following consideration.

Every alternating-current line today has to be provided with extra insulation to withstand the momentary voltage peaks during each cycle—that is, has to be insulated for 1.41 times the nominal alternating-current voltage. Substitution of direct current

instead of alternating current therefore would at once make it possible to raise the direct-current potential up to the full existing insulation of the line,—reducing the current in the ratio of 1.41 to 1 (for an equivalent amount of power transmitted), and so dividing the energy losses by about 2 ($I^2 = (1.41)^2 = 2$).

But the chief difficulty experienced in loading alternating-current transmission lines to their full current-carrying capacity, lies in their impedance, which, amounting to several times the ohmic resistance, results in excessive voltage drop and wide swings in terminal voltage with load changes. To avoid such voltage regulation troubles a-c lines can usually be operated at only a fraction of their actual total current-carrying capacity.

But with direct current, the full current capacity of the line can be utilized, and this gain, together with that resulting from use of the full insulation voltage, means a total advantage of three to six times in power-transmission capacity for direct current as against existing alternating-current lines.

For example, a certain 200,000-volt line transmits 60-cycle alternating current 200 miles into a leading large city. Were this line converted to direct current, the existing insulation would safely withstand a direct-current potential of 280,000 volts. And since with direct current, reactance vanishes, while the ohmic loss diminishes with the square of the voltage ratio, it becomes evident that from three to six times as much power could be transmitted, with comparable performance, at 280,000 volts direct current as at 200,000 volts alternating current. Thus, the introduction of converter and inverter tubes would create the equivalent of two to five additional transmission lines, like that already built.

574. The photoelectric cell: During the discussion of electron emission from solid bodies, in Article 265, it was mentioned that an electron emission may be produced when light rays of certain frequencies or colors are allowed to fall on certain materials, as shown at (E) of Fig. 189. Article 265 should now be reviewed very carefully. The modern photoelectric cell is used in many commercial alarm, control, sorting, and sampling devices, and has been responsible in a large measure for the advances made in the art of television.

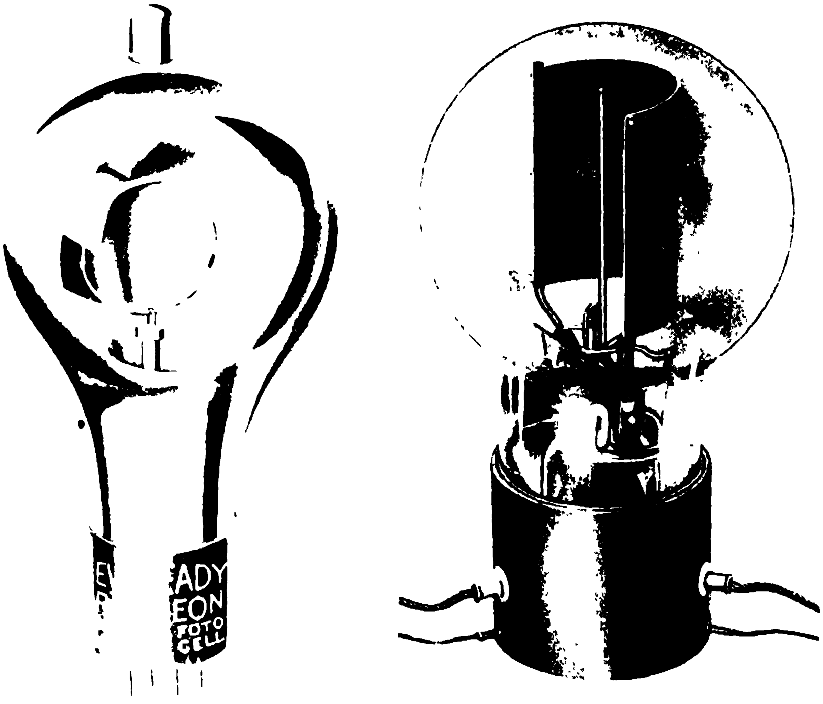
All photoelectric cells depend for their operation on the principle that certain metals, particularly those of the alkali group, have the property of emitting electrons when light rays shine on them. These metals include sodium, potassium, lithium, rubidium and caesium.

Under ordinary conditions, when the surface of the metal is exposed to the air, the emission of the electrons is interfered with by the presence of the larger air atoms. If the metal is put in a vacuum, and a beam of light is then allowed to fall on it, the electrons are free to be thrown off into the space surrounding the metal, and the number of negative electrons emitted per second is proportional to the intensity of the light applied.

If some form of electrode kept at a *positive* potential is put in the vacuum with this illuminated metal, the emitted electrons will be attracted to it and a plate current will flow, as in the case of a vacuum tube. The electrons will continue to be given off and the current due to them will continue to flow just as long as the light is shining on this metal. As soon as the light is cut off, the electron flow stops and the plate current also stops. The current flow will be proportional to the intensity of the light applied to this "active" or "photo-sensitive" metal.

There are really two types of photoelectric cells; one is the *vacuum type*, and the other is the *gaseous type*. In the vacuum type, the space between the photosensitive substance and the anode or plate, becomes conducting due to the pure elec-

tron discharge from the substance. In the gaseous type, which is used extensively in television and sound picture work, there is admitted to the cell during its construction and after a high vacuum has been created, a very small amount of one of the rare gases such as argon, neon, or helium. Such gases, when subjected to the bombardment of the electrons that are released from the photo-sensitive material when the cell is subjected to light rays, become ionized due to their atoms being struck by these rapidly moving electrons. The electrons released from the gas atoms by the ionization separate from their atoms and go to the plate, thus increasing the number between the sensitive material and the plate, and so increase the current flowing. This makes these cells more sensitive to the light. We may regard photoelectric cells as perfect insulators in the dark, and partial conductors when exposed to light.



Courtesy Eveready-Raytheon Corp. *Courtesy Electrical Research Products Corp*

Fig. 436—Left. Photoelectric cell employing a wire-hoop plate inside. This connects to a prong on the base The sensitive coating on the inside of the glass bulb connects to the cap on top The window in the bulb is plainly visible

Right. A type of photoelectric cell used in sound picture work. The sensitive coating is on the inside surface of the curved strip of metal. The "anode" or "plate" is the rod at its center. The two connections are brought out at the bottom.

575. Photoelectric cell construction: Two forms of photoelectric cells are shown in Fig. 436. The one at the left has the bulb mounted on a standard 4-prong vacuum tube base, with the wire-hoop plate or anode visible at the center, connected to the usual "P" prong. This anode cannot be in the form of a wide, solid plate since it would interfere with the light shining on to the sensitive material. Therefore, it is made in the form of a hollow hoop. The inside surface of the glass bulb is coated with a deposit of metallic silver, except for the small round *window* or clear

space, through which the light is to enter. This window is visible in the illustration. A part of the interior surface of this silver coating is covered with a finely divided form of one of the alkali metals already mentioned, or one of their compounds. This acts as the cathode, and makes contact with the silver coating which is connected to the metal cap on top of the glass bulb for connection purposes. This is a gas-filled cell designed for use in television transmitting equipment.

The cell at the right is an improved form designed for use in sound picture projection work. It is of the gas-filled caesium-oxide type, and has a high sensitivity. The light-sensitive caesium-oxide is coated on the inside surface of the semi-cylindrical metal sheet. Electrical connections to the cell are made by means of the two wires shown extending from the Bakelite base. The "positive" rod-type "anode" or "plate" is visible mounted inside of the curved coated-metal sheet. It is claimed that with this construction, a cell of longer life and greater sensitivity is produced.

The active materials used in photoelectric cells are usually the hydrides or oxides of the materials already mentioned. The hydrides and oxides are more light-sensitive than the pure metals, hence are most commonly employed. The sensitivity of the cell to light rays of different colors, depends on the material used. For example, a gas filled cell with a cathode of potassium hydride is very sensitive to visible light with its peak of sensitivity in the blue light region at about 4,500 angstrom units (see the photoelectric spectrum at the lower left of Fig. 163). The caesium cell is sensitive to both visible light and to infra red radiations, and is therefore particularly adapted to use with a light source consisting of a standard mazda lamp. Other materials are sensitive chiefly to ultra-violet radiation. A cadmium cell with a quartz window, is sensitive to the wavelength band of light between 2,000 Angstrom units and 3,000 Angstrom units.

576. Need for an amplifier: Possibly the most simple type of photoelectric cell circuit is shown in Fig. 437.

Here a source of light at the left shines into the window in the cell, on to the active material P (cathode) coated on the inside of the glass bulb. The anode A at the center is kept at a positive potential with respect to the cathode, by connecting it to

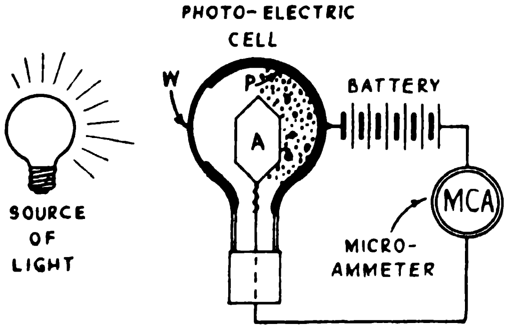


Fig 437—Simple photoelectric cell circuit arrangement in which the intensity of the light shining through the window W on to the photo-sensitive material P of the cell is indicated by the reading of the microammeter in its circuit The anode or "plate" is at "A."

the positive terminal of the battery as shown. Light shining on the active material causes electrons to be emitted. These are attracted by the positive anode, and therefore we have a flow of electrons around through the circuit. This constitutes electric current. Its strength depends on the intensity of the light showing on the cell.

Photoelectric cells are usually employed to indicate or measure changes in the intensity of the light coming from the source. Since the operating current of either a vacuum or gas-filled type of photoelectric

cell is very low as compared to, say an ordinary amplifier vacuum tube, i.e., on the order of a few *microamperes* (millionths of an ampere), a micro-ammeter is shown as the current measuring instrument in Fig. 437. Although it is possible to construct a relay that will operate on such minute currents, it is not as a rule very practical. The variations in the current of the photoelectric cell may easily be amplified greatly by one or two stages of thermionic vacuum tube amplification. The amplifier circuits used are of

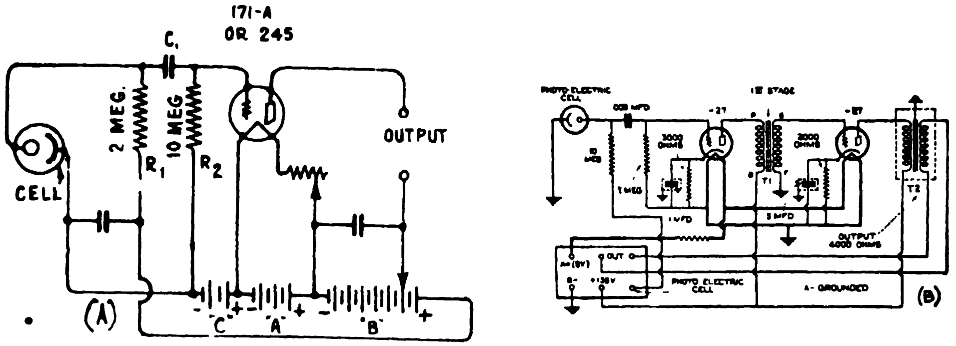


Fig. 438—Left. A simple amplifier circuit for amplifying any rapid current variations in the photoelectric cell caused by changes in the intensity of the light shining on it.

Right· The circuit of an a-c electrically operated combination sound head and sound head amplifier unit employed in sound picture work. The output of this is amplified further by an additional power amplifier.

two general types. In one type, employed extensively in sound picture and television work, the rapid variations in the light are translated into amplified voltage variations. In the other type, the changes in the light are made to produce plate current changes sufficiently great to operate a suitable relay.

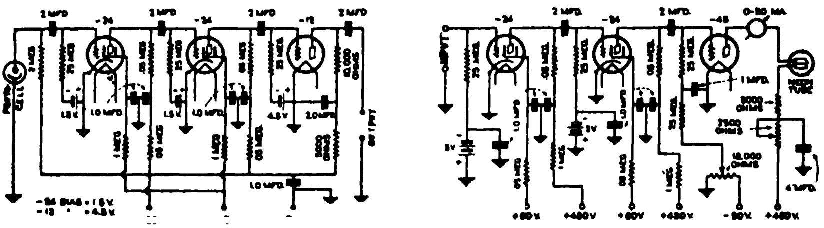
577. Photoelectric cell amplifier circuits for rapid light-variations: A form of amplifier which is adapted to amplify the rapid changes of photoelectric cell current produced by rapid changes in the intensity of the light shining upon it, is shown at the left of Fig. 438. This type of amplifier circuit is used extensively in television and sound picture work.

The photoelectric cell is really in series with the "B" battery, which acts as a polarizing battery to keep its plate positive. A 1 mfd. condenser shunts the "B" battery. Also in series with this circuit is the high resistance R_1, the voltage drop across which, is to be utilized. This is coupled to the grid of the tube, through a blocking condenser C_1, and a grid leak R_2 in the regular fashion used in resistance-capacity coupled amplifiers. This tube should have as low a mu as possible when high frequencies are to be amplified. If the light shining on the cell varies, the current flowing through it also varies. Since this current flows through resistor R_1 and therefore produces a voltage drop across it, this voltage drop will vary correspondingly. This varying voltage existing across R_1 is communicated to the grid of the tube, which amplifies it. This may be followed by another amplifier tube coupled to the first, as shown in the amplifier circuit at the right.

R_1 should be as large as possible in order to have a large voltage-drop available. It must not be made too large, however, as then an appreciable variation in voltage

drop will result and thus affect the positive potential applied to the cell and possibly produce distortion. A low value of R_1 helps the high-frequency response at the tube end. Of course, all wires should be as short as possible and run free from other wires and apparatus. R_1 should be supported by its connecting wires in air to prevent leakage of current.

Upon leaving this first amplifier, the impulses can be amplified in several successive stages to the desired extent. In television this is one of the difficult phases, because generally the initial impulses are so very small that an enormous amount of ampli-



Courtesy Mr C. W. Nason and Radio Engineering Magazine

Fig. 438A—Left. A typical photoelectric cell amplifier used directly at the cell in television work.

Right. A typical audio amplifier designed to amplify uniformly all frequencies from 15 to 30,000 cycles. This is also useful in television work.

fication is required, and tube noises become important. Also, as we shall see later, the amplifier must have a perfectly flat characteristic over a very large frequency-range.

A complete a-c operated amplifier circuit of this type used in sound picture work is shown at (B) of Fig. 438. Notice that two stages of amplification follow the photoelectric cell. The values of all circuit constants are given. T_1 and T_2 are high-grade audio transformers. The 10 meg. grid leak may be made up by connecting five 2-meg. leaks in series. Care should be taken to suspend it in the air to prevent leakage. The output of this amplifier is fed into a large power amplifier for operating the large loud speakers in the theatre. We will study sound picture systems later. A 3-stage resistance-coupled amplifier designed especially to amplify uniformly a band of audio frequencies from 15 to 30,000 cycles is shown following a photoelectric cell used in television work, at the left of Fig. 438A.

578. Photoelectric amplifier circuit for intermittent relay operation: In many commercial applications of photoelectric cells, it is desired to have changes in light intensity cause the cell to operate a relay, which in turn opens and closes a separate circuit in which a counter, alarm, indicator device, etc., may be connected. Two amplifier arrangements are commonly used in this work. In one, an increase in current through the relay results when the light intensity increases. In the other, a decrease in the relay current results. Photoelectric cells used in relay-operated circuits in industrial work are often referred to by the somewhat abbreviated term *phototube.*

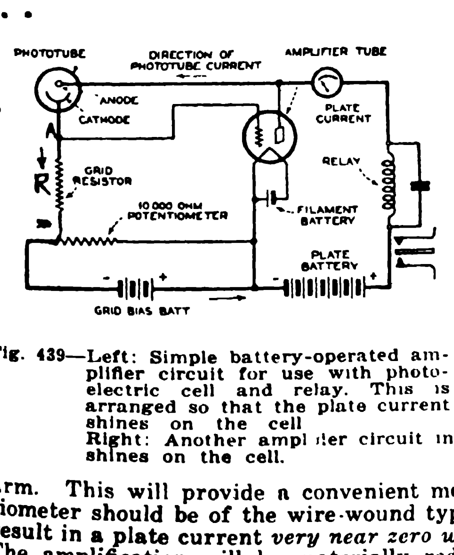
A simple vacuum tube amplifier circuit may be changed to a phototube amplifier by simply connecting the anode (plate) of the phototube to the plate of the amplifier tube, and the cathode (sensitive surface), to the grid, and adding a grid resistor. A simple battery-operated circuit of this kind is shown at the left of Fig. 439. As long

as the phototube is dark, the circuit conditions remain unchanged and the plate current will be determined by the grid-bias potential placed on the tube by the grid-bias battery and the setting of the 10,000 ohm potentiometer. As soon as light strikes the phototube, an additional very small current flows through the phototube and the rest of the circuit, as indicated by the heavy lines. Notice that this current flows through the high-resistance grid resistor R. This current flow produces a voltage drop across it (equal to $I \times R$), and since the current flows downward, point A will be at a higher potential than point B. (Current flows in a circuit from a point of higher potential to one of lower potential), i.e., the negative bias effective on the tube has been *reduced.* Therefore this voltage drop results in making the grid less negative, and so its plate current is increased. The increase in the plate current of the amplifier tube is much greater than the increase in current through the phototube, due to its amplifying properties. If the relay connected in its plate circuit is properly adjusted, it may be made to open or close an auxiliary circuit when the plate current increases due to light shining on the cell.

It is important to note that the phototube current is quite small, and in order to produce a voltage drop large enough to secure the desired change in grid voltage, the grid resistor must have a very high value—from 10 to 200 megohms. The higher values of resistance result in a very sensitive amplifier but which is also quite critical and unstable. Leakage across tube sockets and other insulation becomes a considerable factor for very high grid resistors. A comparatively small amount of electrical leakage will conduct as much as a 100-megohm grid leak and thus upset the operation of the entire circuit. A compromise must be made between sensitivity and stability. A value of 50 to 60 megohms (which may be obtained by connecting 5 or 6 ten-megohm grid leaks in series) will be found to be a good value to use.

In order to make intelligent use of a phototube amplifier circuit, a milliammeter may be used in the plate-circuit of the amplifier tube. Although the current range will depend somewhat on the type of amplifier tube used and its plate voltage, a meter with a 0-25 milliampere scale will probably be found to be about the correct size.

It will also be found very convenient to connect a 10,000- or 15,000-ohm potentiometer across the grid-bias battery, and to connect the grid resistor to its movable



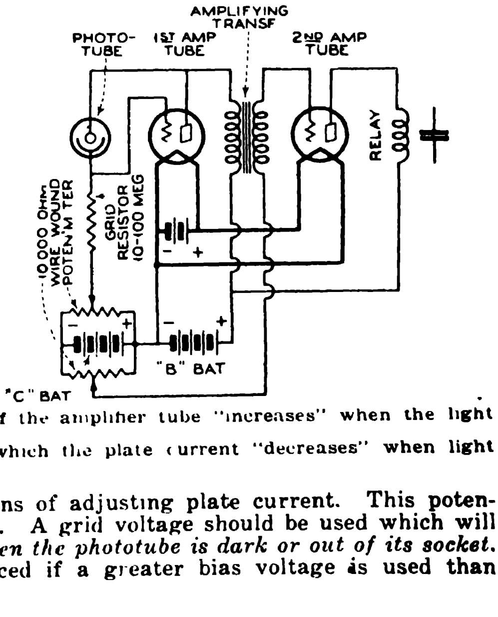


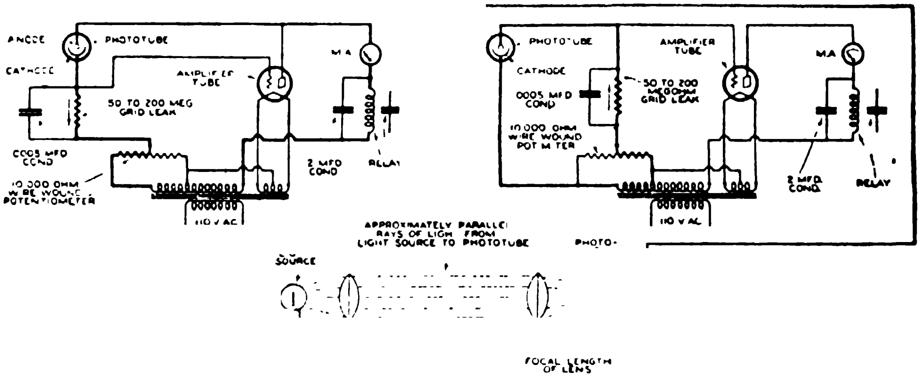
Fig. 439—Left: Simple battery-operated amplifier circuit for use with photoelectric cell and relay. This is arranged so that the plate current of the amplifier tube "increases" when the light shines on the cell
Right: Another amplifier circuit in which the plate current "decreases" when light shines on the cell.

arm. This will provide a convenient means of adjusting plate current. This potentiometer should be of the wire-wound type. A grid voltage should be used which will result in a plate current *very near zero when the phototube is dark or out of its socket.* The amplification will be materially reduced if a greater bias voltage is used than necessary.

A 2-stage transformer-coupled amplifier of this type, for producing stronger impulses is shown at the right of Fig. 439. When the phototube is exposed to light, a

current flows through the grid resistor of the first amplifier tube in exactly the same manner as in the single stage amplifier. This makes the grid more positive and results in a plate current increase. The increase in plate current flowing through the primary of the audio transformer, induces a voltage across the secondary which is applied to the grid circuit of the second tube and is amplified, causing a much larger change in the plate current of the second tube. This current flows through the relay and operates it.

While battery-operated amplifiers are used in many cases, it is frequently more convenient to operate a photoelectric cell and its amplifier from an a-c voltage source than from "A" and B batteries. The characteristics of the circuits given for battery operation are not appreciably changed if the amplifier tube filament is supplied with alternating current and the plate and bias voltages are supplied from any standard "B" eliminator. A circuit that is satisfactory for many applications, although



Courtesy Radio News Magazine

Fig. 440—Left An a-c operated photoelectric tube amplifier circuit in which an "increase" of illumination causes an "increase" in the plate current of the amplifier tube.

Right An amplifier circuit in which an "increase" of illumination causes a "decrease" in the plate current

Bottom A diagrammatic sketch of a simple optical system for use with a photoelectric cell The light source may be a simple automobile headlight bulb

somewhat less sensitive, may be obtained by utilizing "raw" alternating current as a plate and grid-bias supply. When an a-c potential is impressed on a cell and its amplifier, an appreciable current will be conducted only during a portion of alternate half cycles—the result is naturally a lower sensitivity than that obtained in a circuit where the current is flowing continuously.

An a-c operated phototube amplifier circuit arranged to produce an *increase* in the amplifier tube current, when the light on the phototube is *increased*, is shown at the left of Fig. 440. Notice that it is similar in most respects to the battery-operated circuits already considered. The operation of the circuit may be better understood if it is remembered that the devices operate *only* during the periods when the end of the transformer connected to the amplifier tube plate circuit has a *positive* polarity, so as to make the plate positive. When light strikes the phototube, a current flows through the circuit, indicated by the heavy lines. This current, flowing through the grid resistor, makes the grid more positive and causes a rise in the amplifier plate current and operates the relay.

Unless some precaution is taken, the same type of relay that is used in the plate circuit of a d-c operated amplifier, cannot be used with an a-c operated amplifier.

Since a-c voltage is being applied to the plate circuit, the plate current is flowing only during half of each cycle, and even then does not reach a steady value. The relay will attempt to follow the current variations, which will result in a pronounced "chatter". This condition may be prevented by connecting a fixed condenser across the coil of the relay, of about 2 or 4 mfds. This condenser will become charged while current is flowing and then will discharge into the relay coil when current is not flowing, thereby holding the relay closed during the portion of each cycle when current is not flowing.

Another method of accomplishing the same result, is by the use of a "lag-loop" type relay, such as is illustrated at the left of Fig. 443. This type of relay is fitted with a heavy short-circuited turn of copper which has "eddy-currents" induced in it by the magnetism of the relay. The fields created by these eddy currents tends to prevent the collapse of the magnetic flux in the core of the relay during each half cycle, and so prevents "chatter" The fact that this type of relay remains closed for a fraction of a second after the current is shut off, may or may not be a disadvantage, depending upon the characteristics of the device to be operated by the relay.

An a-c operated circuit arranged so that a *decrease* in the phototube illumination will cause an *increase* in the amplifier tube plate current, is shown at the right of Fig. 440. The only difference between this circuit and that at the left is that the phototube is so connected that its current flows through the grid resistor in the opposite direction from that in the arrangement at the left. Therefore an *increase* in the phototube current now makes the grid more *negative*, and so causes a decrease in the amplifier tube plate current, as long as the phototube is illuminated.

The plate and bias voltages in these circuits will depend on the characteristics of the make of the phototube used, as well as the maximum amount of plate current required to operate the particular relay employed. An increase of plate voltage accompanied by a proportionate increase in bias voltage, results in a higher maximum plate current. However, the plate voltage must be limited to the ratings of the tubes used.

579. Light sources for photoelectric devices: In order to employ a photoelectric cell for useful purposes, it is necessary to furnish a suitable source of light, and consider proper methods of directing the light on the cell in order to make it accomplish the particular services required.

In many photoelectric cell applications, the operation is accomplished by the interruption or partial interruption of a light beam from an artificial source. In selecting this, it should be remembered that it is only necessary to direct a small but intense spot of light through the "window" of the light sensitive tube. An incandescent lamp produces light from a heated filament. The filament is heated to practically the same *temperature* for any bulb, from the smallest to the largest. If the image of the filament of a large bulb is concentrated on a phototube, it simply produces a larger spot of light of about the same intensity as a much smaller bulb. This of course means that usually, nothing is gained by using a large bulb as a light source. An ordinary 21-candle power automobile headlight bulb makes an excellent light source for this purpose, since it produces an intense concentrated light.

If the bulb is simply placed in the open, a sufficient light intensity for satisfactory operation will not reach the phototube except for extremely short spacings between the phototube and light source. For greater distances, a parabolic reflector, or simple convex lens placed at a distance from the bulb equal to its focal length, will concentrate the light into approximately parallel rays. If the scheme is to work for distances more than a very few feet, it will also be necessary to use an additional lens in front of the phototube to collect and concentrate the light on the phototube. An optical system of this kind is shown at the bottom of Fig. 440. Plano-convex or double-convex lenses (2 to 6 inches in diameter) of a focal length of from two to six inches will be found satisfactory. A cheap "reading glass" will generally meet these specifications.

The lens in front of the light source should be so placed that a sharp image of its filament will be thrown on a flat surface at about the same distance as it is expected to work the phototube. It will be found that the distance from the bulb to the lens is the focal length of the lens, except for extremely short operating distances. The collecting lens in front of the phototube should be similarly placed at its focal length so that the collected light is focused on a small, intense spot on the cathode of the phototube.

580. Some commercial photoelectric cell control systems: The variety of commercial applications of photoelectric cells in control devices is so varied that no attempt can be made to explain them all here. A few

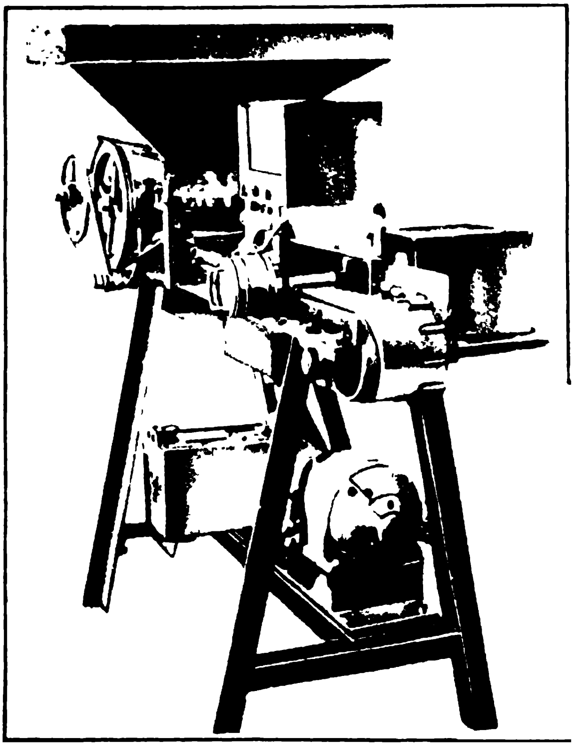
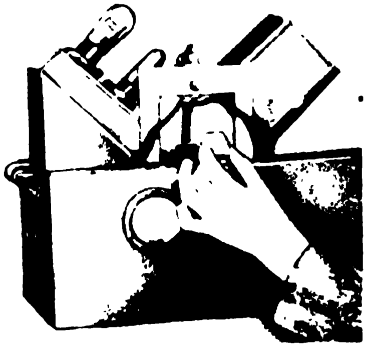


Fig. 441 – Left: A photoelectric counter installed on a machine. It counts the lamp bases which travel along on the conveyer belt.

Right: A sorting device employing a photoelectric cell for sorting light and dark objects. (See Fig. 442.)



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typical applications will enable the reader to see just how the cell is applied, and will possibly enable him to think up further applications.

Photoelectric cells are used extensively for automatic counting of objects. When applied in this way, the light beam usually is arranged to be interrupted by the passage of the objects to be counted. These may come along on a conveyor belt, etc. The interruptions of the light beam, cause the relay in the plate circuit of the amplifier tube to close an auxiliary circuit each time. This auxiliary circuit may contain an electrically-operated counter device. An arrangement of photoelectric cell, amplifier and counter, to count lamp bases as they interrupt a light beam in passing along a conveyor belt after having been produced in the automatic machine, is shown at the left of Fig. 441. The light source is at the left in the small enclosure having a handle on the cover. The beam of light is projected across the conveyor belt to the photoelectric cell in the rectangular box on the right—which also contains the amplifier and counter.

The passage of each lamp base, a few of which are shown on the conveyor belt, interrupts the beam of light and actuates the counter. A similar scheme may be used to count other objects or vehicles passing on a highway, bridge, or tunnel, only in this case the light is usually projected vertically. Systems of this type may also be used for automatic fire detection, and alarm and sprinkler systems, where the presence of smoke reduces the light falling on the photoelectric cell and causes a relay to operate the fire alarm and sprinkler system. Excessive exhaust gas fumes and smoke caused by automobiles in a vehicle tunnel are detected in the same way, the cell circuit operating proper relays to start up the ventilating fans. Burglar alarm systems can also be operated in this way by arranging the light (preferably an invisible ultra-violet or infra-red light source) so the passage of a burglar interrupts it and operates the relay for the burglar alarm system.

Small objects having a decided difference in light-reflecting qualities

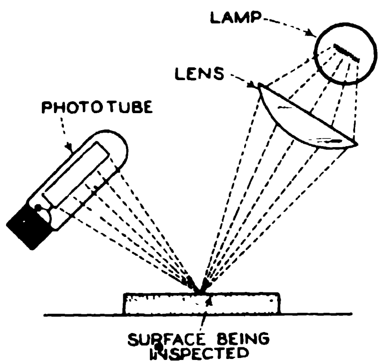


Fig 442—The simple optical system employed in the sorting device at the right of Fig. 441. The light rays from a lamp are focussed on to the surface being tested, by a lens. The reflected light acts on the photoelectric cell

may be sorted by photoelectric means by the use of a simple optical system as shown in Fig. 442.

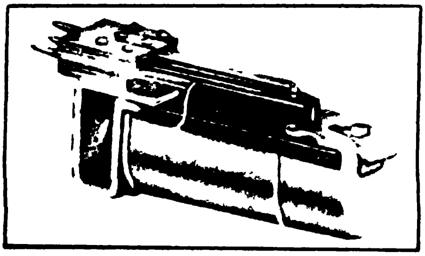
The articles to be sorted may be placed on a conveyor belt and moved into the spot of light. Those articles which reflect a considerable amount of light, will illuminate the phototube sufficiently to cause the operation of a relay, which may be caused to operate an electromagnet so arranged that it will discard such objects; while others having a dull or dark surface, will not reflect light so readily and will pass through. A d-c or properly rectified voltage supply is necessary for schemes of this kind. The setup of a typical commercial sorting device of this kind is shown at the right of Fig. 441. It should be noted that such a device can only be readily constructed to sort objects having a considerable difference in reflecting ability. Special arrangements are required if it is desired to distinguish between articles having a somewhat smaller difference in light-reflection ability.

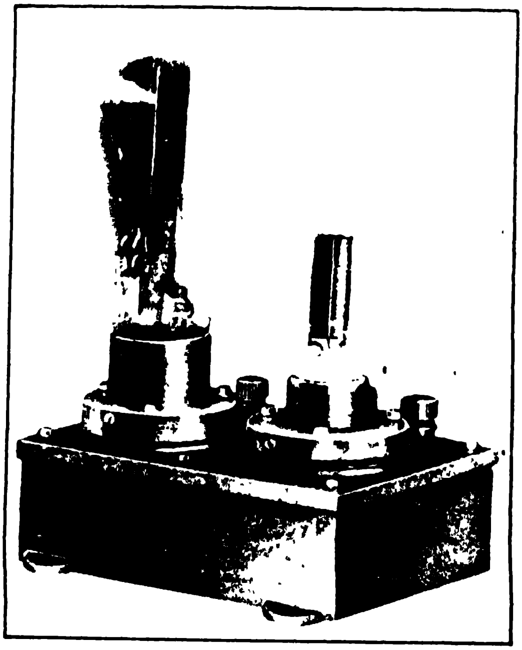
Photoelectric light intensity meters, and color analyzers, in which photoelectric cells sensitive to different colors and a suitable color filter system are used, are employed extensively in many lines of work. At the left of Fig. 443 is shown a lag-loop type of relay used in the plate circuits of a-c operated amplifier systems, and at the right is a typical commercial form of compact photoelectric amplifier unit. The small photoelectric cell is at the right and the amplifier tube is at the left. All necessary coupling and circuit parts for the amplifier are contained in the box below. The particular applications of photoelectric cells in television and sound picture work will be treated in detail in the following chapters devoted to these subjects.

581. Photo-voltaic cells: Another type of light sensitive phenomena is that property which certain materials have of generating a voltage when light shines upon them. This is termed the *photo-voltaic* effect, and this property is exhibited by certain materials, notably copper oxide. This type of cell has generally been considered to be somewhat sluggish in its response to rapid changes of light intensity, but certain improved forms have been developed, that have partly overcome this difficulty. The advantage of this type of cell is that since it actually generates a voltage, in most cases the usual amplifier is unnecessary with it, the cell operating a

Fig 443—Left A "lag-loop" type relay suitable for use in the plate circuits of a-c operated photoelectric amplifiers The flat armature at the right end is attracted by the magnetised core. This pushes up the contact arm of the switch at the upper left, to close the auxiliary circuit

Right: A commercial photoelectric amplifier unit. The photocell is at the right and the amplifier tube is at the left All necessary circuit equipment is in the base.





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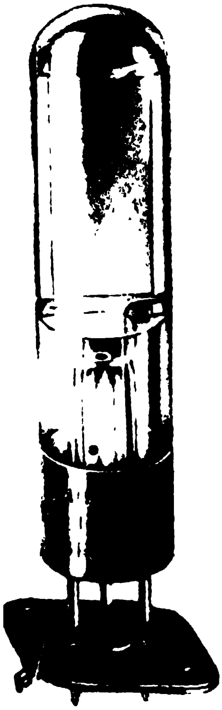
relay direct. Even if an amplifier is necessary, it need not have as many stages as that required for use with the vacuum or gas-filled types of photoelectric cells just described.

582. Radiovisor bridge light-sensitive cell: A new type of light-sensitive cell sold under the trade name of "Radiovisor Bridge", has been introduced in the United States, although originally developed and produced in England. It employs a special form of the element selenium for its operation.

Selenium has long been known to possess the peculiar characteristic of changing (decreasing) its *resistance* when subjected to the action of light rays, but the forms of selenium cells heretofore produced have had the serious disadvantage of being sluggish in their action. The time required for the current flow through an ordinary selenium cell to reach its maximum value when the device is illuminated, is of the order of a number of seconds. The current decrease when the source of illumination is cut off, is similarly sluggish. This feature, more than any other, has been respon-

sible for its very limited application, since it is not capable of satisfactorily respondng to rapid light variations.

In the new selenium-type Radiovisor Bridge, this limitation has been overcome by a special construction, and the resistance changing action of the cell is so rapid that it is capable of responding to interruptions or variations of illumination occurring as rapidly as 10,000 per second.



Courtesy The Burgess Battery Co.

Fig. 444—A Radiovisor Bridge. This is a special form of selenium-type light-sensitive cell in which time-lag has been greatly reduced

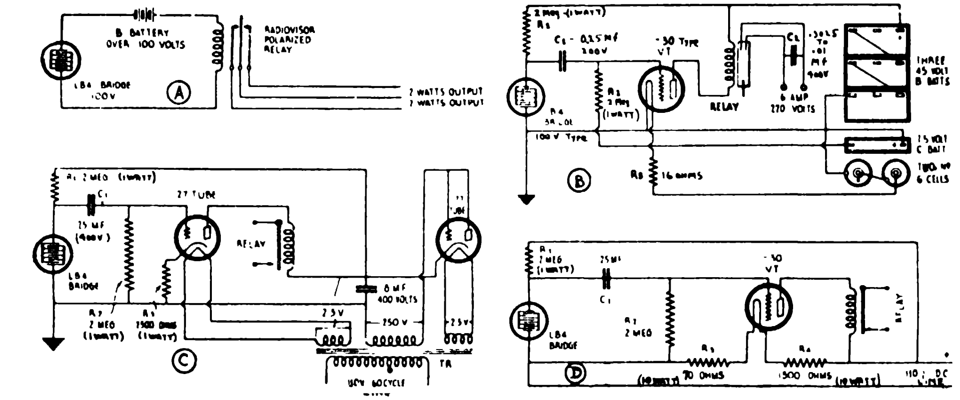
The Burgess Radiovisor Bridge consists of a tall, tubular glass bulb with a three-prong base as shown in Fig. 444. Inside the bulb is a flat plate occupying the center and supported by two heavy lead-in wires. The plate is of glass, upon the front side of which are two interlocking comb-like grids or electrodes of gold, fused in place. These grids or electrodes are covered with a thin enamel of special composition the conductivity of which changes with the amount of light falling on it, thereby providing a light-sensitive cell. The active selenium enamel is spread as a film of the almost infinitesimally small thickness of about .0025 centimeters. This thin layer makes it possible to employ the entire mass, having an active surface about ¾ by 2 inches, for useful purposes, thereby minimizing any useless shunt capacity which might reduce the sensitivity of the bridge. The result is a cell that is claimed to handle many times the current of the usual photoelectric cell, that is highly responsive to light variations, that does not fatigue in continuous use and that does not deteriorate even after long service.

Due to the appreciable amount of current that can be passed through the Bridge, as contrasted with the very limited current passed by the usual photoelectric cell, it becomes possible to utilize simple, practical and quite inexpensive circuits with this Bridge, thereby multiplying many-fold the possibilities of light control. The Bridge can operate a relay direct, for controlling a circuit handling a few watts of electrical energy, while a second relay provided with a novel form of vacuum contact permits of handling several hundred watts for serious work. For more intricate applications, vacuum tubes can be employed, in which event considerably less amplification is required than in the case of the usual photoelectric cell, because of the higher initial current available.

In applying the bridge, use is made of the property of the selenium conductor by which its surface is exposed to light. The bridge, with a dark resistance of the order of 1 to 10 megohms, is connected to a suitable d-c supply in series with a *sensitive relay* so adjusted that the normal current passing through it is just insufficient to close its contacts so long as no light falls on the bridge. When the bridge is illuminated, however, the current is increased well over four-fold, and the relay closes instantly. The sensitive or primary relay may be employed to control a circuit requiring only a few watts of energy. If a greater amount of energy is to be controlled, a *power or secondary relay* is required. This may be of the telephone relay type, utilizing a special vacuum-type contact.

A simple circuit in which the bridge operates a polarized relay directly, is shown at (A) of Fig. 445. This is the simplest battery-operated circuit arrangement for the application of the bridge. The relay may require adjustment from time to time to allow for variations of the resistance of the bridge. An impulse circuit for dry-

battery operation, in which the bridge feeds a '30 type 2-volt vacuum tube, which in turn actuates a power relay, shown at (B). The contact may be of the vacuum type, and is shown beside the relay coil. A basic 110 volt a-c operated impulse circuit with the bridge feeding a '27 type indirect heater amplifier tube, which in turn actuates a power relay is shown at (C). A second '27 type tube rectifies the a-c supply. The detailed operation of these circuits is substantially the same as those



Courtesy The Burgess Battery Co.

Fig 445—(A) Battery-operated, direct-coupled circuit, of a Radiovisor Bridge light cell and a polarized relay
(B) Impulse circuit for dry battery operation with a vacuum tube amplifier and relay.
(C) Impulse circuit for 110 v a-c operation A vacuum tube amplifier and relay are also employed
(D) Impulse circuit for 110 v d-c operation with vacuum tube amplifier and relay

already explained for the photoelectric cell, in Article 578. An impulse circuit for 110-volt d-c operation employing a '30 type 2-volt tube amplifier, and power type relay is shown at (D). If the circuit is to be operated from a 220 volt d-c line, R_4 should be changed to 3,000 ohms.

REVIEW QUESTIONS

1. What is the main difference in the operating characteristics of an ordinary high-vacuum tube such as is used in the amplifier of a radio receiver and a thyratron tube? What special construction features of the thyratron tube are responsible for this?
2. Explain the operation and principle involved in an oscillator system designed for accurate measurement of weights, thicknesses, etc.
3. What is the difference between the principle of operation of a photoelectric cell, a photo-voltaic cell, and a selenium light cell?
4. Explain why gas-filled types of photoelectric cells are more sensitive than the vacuum type.
5. Explain the construction (with sketches) of a commercial form of photoelectric cell.
6. What is the purpose of the active material; the plate or anode; the window? Name four "photo-sensitive" materials.

7. Draw the circuit diagram of a single-tube battery-operated amplifier for a photoelectric cell, arranged to produce a *decrease* in the amplifier plate current when the light intensity increases.
8. Explain the operation of this circuit in detail.
9. Explain how leakage could take place across the grid resistor terminals, and just what effect this would have on the operation. How may this leakage be minimized?
10. Draw a schematic sketch showing the photoelectric cell and amplifier and all equipment you would employ for automatically counting the number of automobiles going in a single direction over a certain road. The entire apparatus is to be operated from a 110 volt a-c lighting circuit. Explain its operation.
11. Repeat Question 10 for an installation in which black shoes are to be sorted from white shoes.
12. Repeat Question 10 for an installation on a newspaper printing press, printing on a continuous sheet from large rolls of paper. The photoelectric cell device is to actuate the line switch of the printing press motors to immediately stop the press if the paper should suddenly break.
13. Describe the selenium Radiovisor Bridge type of light cell. How does this differ in operation from a photoelectric cell?
14. Draw a circuit diagram for a complete a-c electrically operated Radiovisor Bridge light cell circuit to count the number of bottles of milk coming along on a conveyor belt from a bottling machine.
15. Draw a circuit diagram and complete apparatus arrangement for a photoelectric cell and 3-stage a-c operated audio amplifier circuit feeding to an electrodynamic type loudspeaker. The photoelectric cell is to be arranged to respond to the rapid variations in the light coming to it from a steady source of light interrupted by a series of dark and light bands on a strip of motion picture film moved rapidly between the light source and the photoelectric cell. (Note: This is the arrangement used for the reproduction of the sounds in the sound-on-film system of sound motion pictures.)
16. Explain how the method of emitting electrons in an ordinary vacuum tube differs from that employed in a photoelectric cell.

CHAPTER 33.

TELEVISION

PRESENT STATUS OF TELEVISION DEVELOPMENT — WHAT TO EXPECT IN THE FUTURE — THE RADIO TELEVISION SYSTEM — PERSISTENCE OF VISION IN TELEVISION — HOW THE PICTURE MAY BE SLICED INTO SQUARE ELEMENTS — DIVISION OF THE SCENE INTO STRIPS FOR TELEVISION — THE USE OF THE PHOTOELECTRIC CELL — TRANSMISSION FREQUENCY BAND REQUIRED — THE SCANNING DISC — SCANNING METHODS — SYNCHRONIZED TELEVISION AND SOUND TRANSMISSION — GENERAL TELEVISION TUNER AND AMPLIFIER SYSTEM — THE RADIOVISOR — THE NEON TUBE — THE RECEIVING DISC — SYNCHRONIZING THE DISCS — OPERATING A DISC TYPE TELEVISION RECEIVER TYPES OF SCANNING DISCS — THE MECHANICAL AND THE CATHODE RAY SYSTEMS — THE CATHODE RAY TUBE — THE FARNSWORTH CATHODE RAY SYSTEM — FUTURE OF TELEVISION — REVIEW QUESTIONS.

583. Present status of television development: In its broadest sense, the word *television* has come into general use as a term to indicate the instantaneous transmission of images of objects and scenes, either by radio or by wire. This does not include the art of transmitting photographs by telegraphing (phototelegraphy). While, generally speaking, television includes the transmission of visual scenes by wire, most of the recent development work has been along the lines of transmission without wire lines, although it is not at all improbable that television programs transmitted over existing telephone or electric light circuits may become popular at some future date. Our study will be confined to television by radio.

While the average layman believes that television is an entirely new art brought on by the development of radio, it is interesting to note that the history of television dates back as far as 1873 when the light-sensitive properties of selenium were discovered. Scientists immediately tried to apply this discovery to the solution of the age-old problem of transmission of pictures and scenes. In fact, the principle of the scanning disc, which is still used in one form or another in most television systems, was invented way back in 1884, nearly 50 years ago, by Nipkow, a German. While many more dates and references of early work in this field could be made here, these two will perhaps convince the reader that the idea, and attempts to achieve television transmission and reception are not new by any means. All of our present systems, with the exception of the cathode ray method, are merely improvements on the systems devised many years ago, these improvements being made possible by the develop-

ment of such devices as photoelectric cells, thermionic tubes, neon lamps, cathode ray tubes, high gain amplifiers, etc., which were really developed in connection with other arts.

Any attempt to write a text on television at the present time, must necessarily be confined to a description and explanation of the operation of the various main systems now in use—imperfect as they are. The author will possibly lay himself open to criticism from some readers, when he states that no system thus far presented has been proved capable of achieving really satisfactory and practical television transmission and reception on a commercial basis.

The requirements for satisfactory performance for home reception, which the author has in mind when making this statement are as follows: (a) The picture projected on the receiving screen should be at least 1 foot square, (b) The detail should be at least as good as that of ordinary newspaper photograph reproductions, (c) The light used for the received picture should be of a nature which will not tire the eyes, and all flicker should be eliminated. (The pink light of the common neon tube usually employed, is about as poor a light source from this point of view as could possibly be used). (d) The receiving equipment should not contain any rotating or moving parts and should have a reasonably long life. (e) The radio transmission channel required should not be over 100 kc, unless transmission on the very short waves is resorted to. (f) The receiving equipment should be fairly inexpensive, certainly the total cost should not be very much over that of an average good radio receiver.

No such system has appeared at the time this is written, although the cathode ray system holds forth considerable promise of being capable of sufficient improvement to meet these requirements.

Anyone who is at all familiar with the technical details and results accomplished by the various systems now in use, must agree that these requirements have not been met by any one system to date. No doubt this will cause a distinct surprise and disappointment to the many whose ideas on the subject have been gained by misleading fantastic dreams and writings of many newspaper feature writers and press agents of manufacturers interested in the sale of television equipment. These writings have placed the large mass of the public in the wrong frame of mind regarding television. They have been led to believe that it is an accomplished fact, and that all of the problems have been solved. Naturally they expect perfect television reception. The true story is that hundreds of men are feverishly engaged in research work almost day and night in the laboratories of the world, in attempts to solve some of the problems which the newspaper writers have apparently solved with a few clicks of their typewriter keys. The public should be made to realize that television today is still in the development stage. This is no disgrace—every art must pass through this stage. The unfortunate difficulty is, that false reports have placed the expectations of the public way ahead of the actual accomplishments of the research engineers and inventors. There is no doubt but that the intense public interest has had a beneficial effect in spurring on research in this field, but public demands for a finished product, at a time when a really satisfactory system has yet to be found, are rather disconcerting.

584. What to expect in the future: What the future will bring in this field, or how long it will take for successful television to arrive, no one knows. The technical problems involved are by no means simple or few. Even the results now obtained are really remarkable, when we consider the obstacles which block the path to successful television. The various workers in this field are to be sincerely congratulated on their persistence and ingenuity. We must be patient, and not expect too much, for television is still but an infant in growth even though old in years.

Since the art of television is still in the formative process of development, the author feels that the interests of the student can best be served by an explanation of the operation and the principles involved in the various systems in use today, with some illustrations of the actual apparatus employed. This will furnish a background for future study and enable the student to keep up to date on the many developments which are bound to come, possibly in the very near future.

585. The radio television system: All radio television systems are electrical in their nature, just as all radio broadcasting systems of sound are electrical. It will be remembered that in our ordinary sound broadcasting systems, as shown at (A) of Fig. 446, the succeeding sound

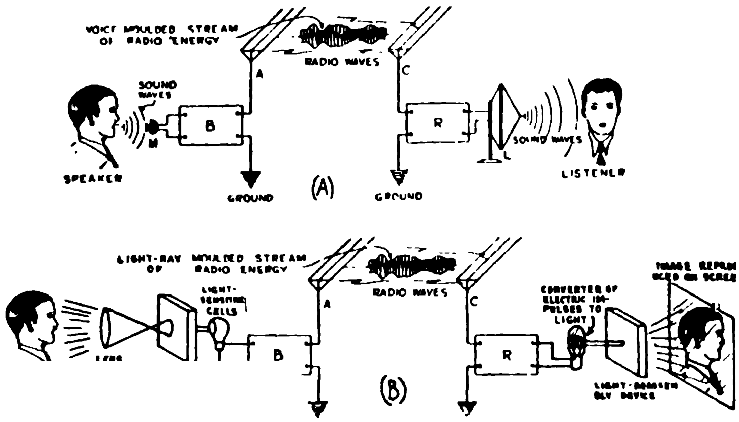


Fig. 446—(A) The typical transmitting and receiving system employed for radio telephone communication This system starts with sound waves which are to be transmitted All of the transmitting, amplifying and receiving is done with electrical impulses. Finally these are converted back into sound waves again by the loud speaker.
(B) The typical system employed for television. This system starts with reflected light rays from the object being televised All of the transmitting, amplifying and receiving is done with electrical impulses Finally these are converted back into light rays and re-assembled to form the visible picture.

waves produced which follow one another rapidly, are allowed to strike the diaphragm of the microphone M in the transmitting station, and be converted into electric impulses which are amplified and caused to modulate a high-frequency carrier current suitable for radio transmission by the transmitting apparatus B. The signals are radiated in the form of varying electromagnetic radiations which induce corresponding modulated high-frequency electrical impulses in the receiving antenna C These are tuned out from those of all other stations, amplified, demodulated, and possibly amplified further by the receiving equipment R. Finally they are converted back into sound waves by the loud speaker L. This completes the system, (see Chapter 15).

In television, the general system is similar, as shown at (B) of Fig. 446, only instead of dealing with *sound waves* at the beginning and end of the system, we deal with

light rays. The first step is the so-called *scanning*, or progressive and systematic optical analysis of the scene to be transmitted. The next step is the conversion of the light impulses thus obtained, into corresponding electrical ones, by means of the photo-electric cells. These electrical impulses are amplified and caused to *modulate* a high-frequency carrier current suitable for radio transmission by the transmitting apparatus B. The signals are radiated in the form of electromagnetic radiations which induce corresponding modulated high-frequency electrical impulses in the receiving antenna C. These are tuned out from those of all other stations, amplified, demodulated, and amplified further, in the receiving equipment R. These electrical impulses are finally re-converted into *light* rays by the light source, and are then re-assembled in a progressive and systematic order to form the image of the original picture transmitted. Notice that the process at the receiver is the reverse of that at the transmitter.

Notice the similarity between this and the sound broadcasting system at (A). In fact, the transmitting equipment exclusive of the scanning and photoelectric cell units, and the receiving equipment exclusive of the light producing and re-assembling device are almost of exactly the same types as those used for regular sound-radio communication—differing only in the several design details required for handling a rather wide modulating-frequency range. Now perhaps the "mysteries" of television are beginning to fade away somewhat from the mind of the reader! We will now study the problems involved in conversion of the reflected light rays from an object into corresponding electrical impulses at the transmitter, and the conversion of these back into the complete scenes at the receiver.

586. Persistence of vision in television: If it was desired to transmit simply "still" pictures by television, the problem would be greatly simplified. Actually however, the pictures of moving objects must also be transmitted and reproduced. Since changing scenes are also dealt with in the ordinary motion picture, let us see how the problem is solved there. This will shed some light on our problems in television transmission and reception. Let us first consider a very important characteristic of the human eye.

When light enters the normal eye it is focused on to the retina by the eye-lens. This retina is coated with a material known as the *visual purple*, in which are embedded the so-called *rods* and *cones* at the nerve ends. According to one theory, when light falls upon the visual-purple, a photoelectric action takes place, and electrons are freed much as they are in a photoelectric cell. These freed electrons set up currents in the visual-purple which are detected by the rods and cones. These in turn set up electric currents in the nerves that carry them to the brain and produce the sensation of sight. The exact action in the brain is still unknown. The nerves are the circuits that carry the message to the brain. The eye interprets different wave-lengths or frequencies as color. Notice the remarkable similarity between this system and an ordinary vacuum tube radio receiver with its tuning circuits.

One exceedingly important characteristic of the eye, is that it does not respond at once to any change in light intensity, but has a lag of about 1/10 of a second and retains an impression for this definite period. Due to this, it is possible to produce the sensation of continuous motion by viewing a moving object successively at intervals of 1/10 second or less.

This is called *persistence of vision*, and is made use of in the projection of motion pictures. On the other hand, an impression must affect the eye for a certain definite

minimum of time, depending upon the intensity of the light, or it will not register on the consciousness at all. To see any moving picture or scene by this method then, the eye must see each scene for a period long enough to awake the consciousness (at least one five-hundred thousandth part of a second if strongly illuminated), and must follow one another at least 1/10 of a second apart. In the projection of motion pictures, the film consists of a series of individual pictures which pass down in front of the light source at a speed of about 16 per second. Each scene or "frame" is jerked down in front of the lens by a special intermittent-motion mechanism, remains stationary there for a short period, then the blade of a rotating shutter comes around and shuts off the light from the scene while the film is being jerked down to the next frame, etc. In other words, each image of the picture flashed on the screen, persists on the retina of the eye for the full time during which the light is cut off, the next *frame* or picture is jerked into place in front of the lens, and the following picture flashes on the screen, etc.

The absolute darkness which exists when the shutter cuts off the light during each jerk of the film is not noticed at all, and the sensation of a continuously moving scene is impressed on the brain. This might be termed, "deceiving the eye".

All television methods thus far developed make use of this action of "deceiving the eye". An electrical impression of the entire scene to be transmitted, (the scene is actually sliced into thin strips as we shall see), is taken, transmitted, and reproduced on the screen at the receiving end almost simultaneously 20 times every second in most systems in use at present. In this way the entire picture is reproduced on the receiving screen 20 times every second, each view differing slightly from the previous one due to the movements of the object televised, and the persistence of vision of the eye makes it appear as a continuously moving picture in exactly the same way as in the case of cinema or motion pictures.

587. How the picture may be sliced into elements: In the motion picture, the entire scene is present on the small picture or "frame" on the film in front of the lens at any instant, and is flashed on to the screen as one complete single picture or impulse. In television, it has not been found possible to transmit the whole scene at once in a single impulse (20 times a second), because no system or device for recording and reproducing the individual light and dark elements of the picture all together in this way, has yet been developed. Instead, each 1/20 of a second the "scanning" device scans the entire scene in narrow "strips" or "slices" starting at the top and working down toward the bottom (see Fig. 448). The "light" and "dark" impulses constituting each strip are transmitted progressively and these light impulses and strips are re-constructed in proper order on the screen at the receiver, persistence of vision again aiding us in making the individual strips appear as a single composite picture.

Experiment: Many simple experiments may be performed to illustrate the persistence of vision. If the glowing end of a match is twirled around, the glowing spot changes its position so rapidly that the persistence of vision of the eye makes it appear to be a bright ring of light. Draw a fish on one side of a white card and a gold fish globe on the other directly in back. Now fasten a string to two opposite edges of the card and twist or twirl it rapidly by blowing on it so as to make it rotate. The fish will appear to be in the globe.

Just how a picture may be broken up into tiny elements and still appear like a solid picture to the eye, may be appreciated by examining closely with the eye alone,

or with a magnifying glass, any half-tone reproduction in this book or in a magazine. It will be seen that what ordinarily appears to be a uniform picture, really is made up of a large number of tiny dots of ink of various sizes and shapes. Fig. 447 is reproduced here especially for a study of this. When a half-tone cut is made, the subject is photographed through a screen consisting of a transparent substance with opaque lines ruled closely on it to form tiny squares. The half-tone cut which is made, also contains these tiny squares, and the tiny square impressions really constitute the reproductions. It will be seen from the illustration at the left, which is made through an exceptionally coarse screen especially for this study, that in the light portion of the picture, these tiny spots of ink are very small. In the darker parts on the hair, coat, vest, and necktie, they are very much larger, and in some places run so close together as to merge into one another. As shown by these illustrations made through screens of different coarseness, the general effect produced by

Fig. 447—The detail of the reproduced picture depends upon the number of picture elements used per unit area. At the left is a half-tone reproduction made up of individual dots of ink (picture elements) spaced 50 to the inch. There are 2,500 such elements per square inch in this. At the center is the same illustration made up of individual dots of ink spaced much closer i.e., 85 per inch. At the right there are 120 dots to the inch. Notice the poor detail of the picture at the left as compared to that on the right.

the entire assembly of tiny dots depends on how fine-grained a structure is used. The picture at the left, which seems rather coarse and lacks detail, was made through a screen having 50 horizontal and 50 vertical lines to the inch, i.e., 50×50 or 2,500 squares or elements per square inch. For the center picture, an 85 line screen was employed. This gives 7225 squares or elements per square inch. That at the right was made with a 120-line screen giving 14,400 elements per square inch. If you stand off with your eyes about 12 inches from the book you will see that the squares in the one at the left are plainly visible, those in the middle are just barely visible, and those at the right cannot be distinguished. Notice how the *detail* of the picture is lost when the tiny picture elements are coarse. For ordinary reproduction, a picture composed of some 17,000 dots to the square inch, (130 rows per inch), leaves little to be desired in the way of detail. The usual newspaper reproductions contain 4,225 dots per square inch (65 rows per inch). A picture composed of some 400 dots per square inch (20 rows per inch), is barely passable even when viewed at a distance of 18 inches or so. In the present television systems using scanning disks, 60 lines or elements per inch are employed.

It is evident from this discussion of half-tone reproductions, that in television, it is really not necessary to transmit and reproduce the entire scene as a single unit each 1/20 of a second. We may split up the scene viewed by the television transmitter, into elementary dots, transmit elec-

trical vibrations corresponding to the brightness or darkness of each individual dot, and reproduce the dots in the same relative order and position at the receiving end. Then our received picture will be made up of a number of dots similar to a half-tone, and if the elements are small enough it will be acceptable. This system has actually been used by Dr. Ives at the Bell Telephone Laboratories, but since a separate circuit was necessary for each element or dot (2,500 circuits in all in this particular apparatus), the system was very complicated and commercially impractical.

588. Division of the scene into strips for television (scanning): In most television systems now in use, the scene is not scanned in the form of dots but in *strips*, by a suitable *scanning device* in the transmitter. At the receiver, these strips of the scene are reproduced in proper order to form the complete scene. The principle of strip-scanning may be understood from a study of Fig. 448. At the left, we have a simple scene or picture to be transmitted. This consists of light and dark areas. Suppose we view this picture through the small square opening shown at the upper left-hand corner of the picture, and that this opening is moved horizontally to the right in the direction of the arrow. We will then view or *scan* the top strip number 1. We now move this square peep hole down a distance equal to the height of this strip, and again move it across the picture from left to right scanning another strip number 2. This will appear as top strip number 2 shown at the right. This operation may be repeated until the entire picture has been scanned or divided into strips which will appear successively as numbered at the right. It is seen, that if all the individual strips at the right were assembled close together, they would form the original picture. Now suppose it were possible for us to scan *all* of these strips in this picture in less than 1/10 of a second. We would not see them as individual strips, because the persistence of vision would cause us to retain the impression of the first strip and the succeeding ones up to the time when the last one was scanned. Therefore, we would see the entire picture as a unit. This is the basis of the television systems now in use. We have considered here, a "still" picture. Suppose the scene were continuously changing? In that case if we scanned the entire picture in at least 1/10 of a second, we would be scanning the entire picture 10 times or more every second, which is sufficiently fast to just enable the persistence of vision to retain the impression of one picture until the next one has been received. The eye would then receive the impression of motion of the scanned objects just as in the case of the motion picture. In practice it is desirable to scan the pictures more rapidly than this, 20 times per second more being used in most television units at the present time.

In actual television scanning, the scanning strips are very much narrower than shown in Fig. 448, 60 lines or strips to the inch now being common in disc scanning systems. Of course the greater the number of scanning strips, the greater the detail of the picture. Considering any one of these very narrow strips, it is found to be

composed of a succession of parts which vary in the amount of light and shade, or in the amount of light reflected at the various points by the image.

The actual total area scanned is called a "frame". Thus in Fig. 448, the entire picture at the left would compose a frame.

589. The use of the photoelectric cell: Now that we have considered a method of breaking our picture or scene up into a number of fine elementary strips, the next problem is to convert the successive light and dark variations in each strip scanned, into corresponding variations in an electric current. This extremely delicate and important operation is performed by the photoelectric cell which we have already studied in Chapter 32; or some other form of suitable light-sensitive cell.

If we arrange in some way for the light reflected from each elementary area in every strip of the scene scanned to fall upon the sensitive surface of a light-sensitive cell, the cell will respond to the variations in the intensity of the light, and may be

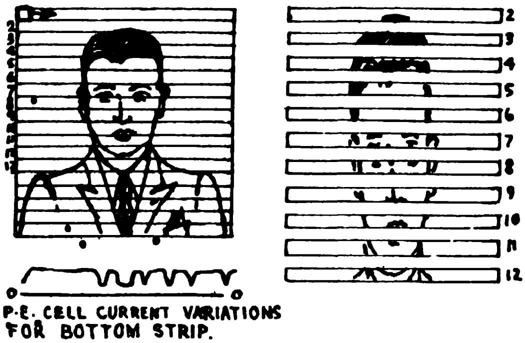


Fig 448—Strip scanning. The scene is rapidly scanned in very narrow horizontal strips. The variations in the light and shade in each strip are converted into corresponding electrical impulses by the photoelectric cell. These electrical impulses are transmitted. At the receiving station they are re-converted back into varying light intensities which are reconstructed in strips somewhat as shown at the right. This is done rapidly so as to appear as a complete scene to the eye. Of course the strips actually overlap slightly.

arranged to produce corresponding variations in the voltage or current of an electric circuit. For instance, if the reflected light coming through the moving square peephole at the left of Fig. 448 were focussed on to a photoelectric cell, it is evident that each light and dark area of each strip scanned, would cause a corresponding variation in the cell current. When a light area was scanned the cell current would increase, when a dark area was being scanned, the cell current would decrease. The variations in the cell current for the bottom strip at the left, would appear somewhat as shown below it, O-O being the axis line for the cell current. Thus the light-sensitive cell in the television system corresponds to the microphone in the sound-broadcasting system, in that it produces the variations in the current. The variations in the cell current are amplified by a very high-gain multi-stage resistance-coupled amplifier of the general form shown at the left of Fig. 438A. This must be designed to amplify uniformly, an unusually wide band of frequencies, and all circuits must be laid out carefully and shielded to prevent feedback.

590. Transmission frequency band required: Let us see just how wide the frequency band will be for standard 60 lines per frame—20 frames per second scanning, assuming the picture to be but 1-inch square. We will assume that the detail of the picture horizontally, is to be as good as that vertically. The worst possible case would then be when there is a variation in light intensity for every 1/60 of an inch horizontally along a scanned strip. This means that the picture elements are so irregular, that a partial light or dark portion occurs in every 1/60 of an inch along the horizontal strip. There will then be 30 impulses produced during the

scanning of a *single strip,* since it takes one complete light variation from light to dark to light through two elements, to correspond to a complete a-c cycle. Therefore, 60×30 or 1800 impulses are produced during a single scanning of the *entire picture.* Since it is completely scanned 20 times every second, there will be $1800 \times 20 = 36{,}000$ impulses in the photoelectric cell circuit every second for this condition. Building high-gain amplifiers to amplify uniformly a band of frequencies up to 36,000 cycles is no simple task, and the resistance-coupled type amplifier is the only type which can be designed to do this. The lowest frequency of this picture frequency is 20 cycles. The amount of distortion present in transformer-coupled a-f amplifiers, while not serious in ordinary sound broadcasting, makes them absolutely unsuited for television work A special resistance-coupled amplifier which will amplify uniformly all frequencies from 15 to 30,000 cycles is shown at the right of Fig. 438A. This circuit should be studied carefully at this point.

The varying output of the photoelectric cell is amplified and made to modulate the high-frequency carrier current in the usual way. Since each television station transmits a carrier frequency and a rather wide sideband, about 36 kc on each side of the carrier frequency in the case here considered, or a total sideband of 72 kc, television stations have been assigned to transmit on the short waves between 100 and 150 meters in the United States, in order to avoid conjestion. At the present time, each station is allowed a transmission channel of 100 kc. Compare this with the 10 kc channels assigned to sound broadcasting stations. Also, since television signals are transmitted by short waves, the ordinary broadcast band receiver used for sound programs is not suitable for television reception. It is not suitable anyway, because the transformer-coupled audio amplifiers used in these receivers distort entirely too much to permit of their use for amplifying television signals.

591. The scanning disc: To carry out the process of "strip scanning" we have been considering, some form of scanning device for rapidly scanning successive strips of the scene must be employed. Perhaps the simplest and most widely used form of scanning device now used in one form or another by practically all television transmitters and receivers, (excepting those employing the cathode ray principle), is the Nipkow scanning disc, invented in 1884, and shown in its most elementary form at the left of Fig. 449. This is an ordinary circular disc containing a series of small holes (or lenses), arranged in the form of a spiral (or several spirals).

Each of these holes is as far from the following one as the width W of the picture to be reproduced at the scanning disk at the receiving end, so that only one hole is actually scanning the scene at a time. The "pitch" or distance of the center of each hole from the center of the disc, differs from that of the next by the diameter of the hole itself—which is the height of the strip scanned. Round holes are shown in this disc. In practice, it is preferable to make the holes square or rectangular to permit more light to pass through to the photoelectric cell, and the holes are arranged so that the strips they scan, slightly overlap each other. This reduces the tendency to produce "lines" or "streaks" across the received picture where one scanned strip would just meet the one above and below it. As the disc rotates, one hole after another sweeps over the field of view of the scene—each hole scanning a slightly curved strip, as shown in the enlarged section at the right of Fig. 449. Since each hole is nearer to the center of the disc than the preceeding one, it scans a strip next to the one scanned just before it. In this way, the entire scene is scanned completely 20 times every second. The visual slicing up of the scene during the scanning action is indicated in the enlarged view at the right, by the curved lines which represent the boundaries of the strips scanned. The manner in which the photoelectric--cell current

might vary due to the variations of light impressed on it during the scanning of some one strip, is shown below. In the illustration at the right, the picture is scanned in 39 narrow strips (39 lines).

As we shall see later other forms of discs with two or three sets of holes may also be used. Also the disc may take the form of a belt or drum. The cathode ray system of scanning and reproduction is so radically different from the ordinary disc scanning system that it will be considered separately later.

592. Disc scanning methods: There are three methods of using the disc for scanning the scene to be transmitted. These are, *film pickup*,

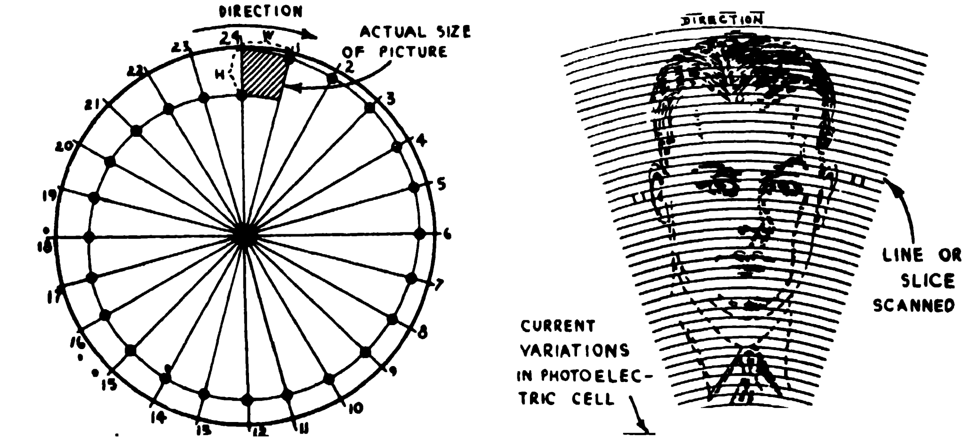


Fig. 449—Left: Layout of the holes in spiral form in a circular 24-line scanning disc. The shaded area represents the size of the reproduced picture at the receiving station.

Right: How a scene is scanned over curved strip paths by a circular scanning disc. This is an enlarged view, and is drawn for 39-line scanning, i.e., there are 39 scanning strips for the entire scene Every time a black part of the scene is viewed by the photoelectric cell, the cell current drops. The variations in the cell current during the scanning of one particular strip of the picture on the right are shown at the lower right

direct pickup, and *indirect pickup*. Pickup from a moving picture film has become popular, since the film is taken under ideal conditions and it presents a very small area to be scanned, an area which can be brightly illuminated with much more light than can be comfortably thrown on a person sitting in front of a television camera.

The direct pickup method uses what might be termed a "television camera". It is a scanning arrangement, photoelectric cell and cell amplifier mounted on a strong tripod with a very fast lens picking up the light reflected from the illuminated object to be televised. The rapidly moving holes in the scanning disc allow one pencil or strip of this light at a time to pass through to an ultra-sensitive photoelectric cell mounted behind the disc. The current variations in the photoelectric cell, caused by the light and dark variations in the light projected on it, are transformed into similar voltage variations, and amplified by the amplifier mounted at that point. This builds them up to a sufficient strength to be sent to the radio transmitter itself, where they may be amplified further, and made to modulate the carrier current of the station in the regular way. This system is shown at the left of Fig. 450.

This method is most successful for outdoor work, since there is plenty of light available. For indoor work, however, it requires very intense artificial lighting

which is extremely trying on the artists performing before the televisor. The intense heat produced by the battery of lights employed for the floodlighting of the performer is rather uncomfortable.

This problem has led to the development of the indirect pickup method, which is now widely used. This is commonly called the "flying spot" method.

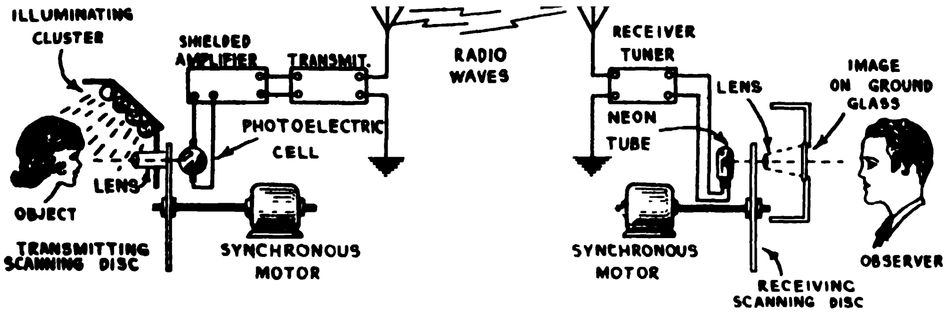
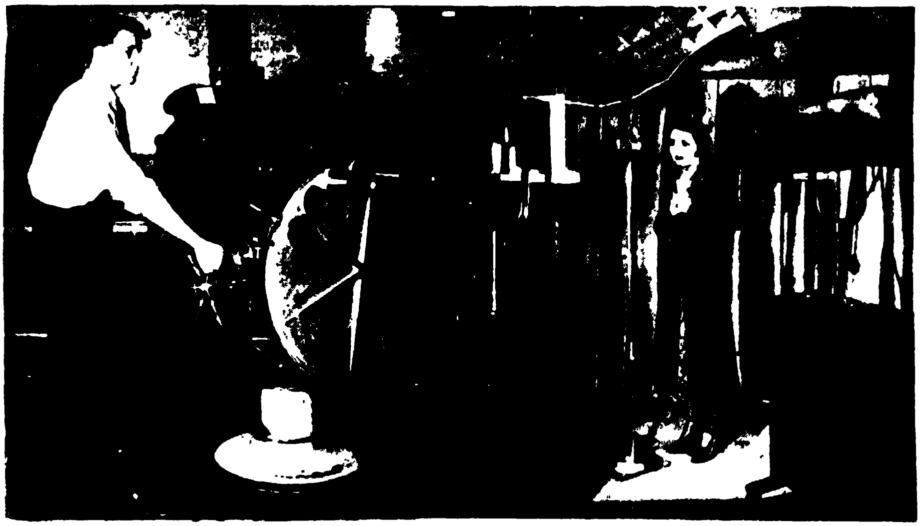


Fig. 450—Television transmitting and receiving system using the scanning disc method The direct pickup system is used in the transmitter at the left. Light reflected from the strongly illuminated subject is picked up by a suitable lens system and directed through the whirling holes in the scanning disc and focussed on to the sensitive material in the photoelectric cell.

In this system, the scanner comprises a powerful arc lamp fitted with a scanning disc driven by an a-c synchronous motor, and a battery of lenses of different focal lengths so as to provide different sizes of fields. The assembly is mounted on a swivel base similar to that of the usual barber's chair as shown at the left of Fig. 451, so as to permit of aiming the beam at the subject. By swinging any desired lens into posi-

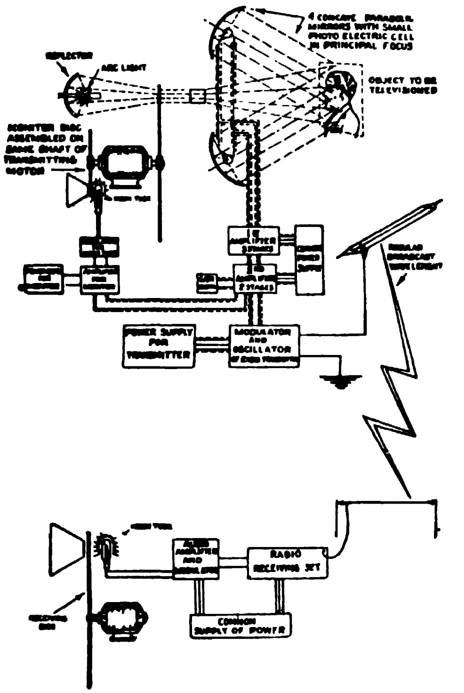


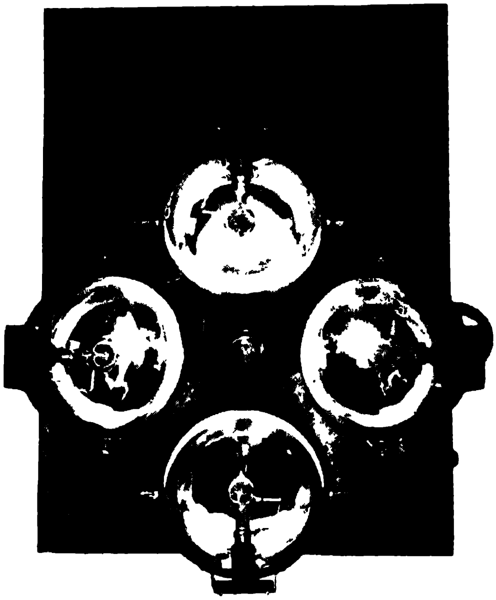
Courtesy The Jenkins Television Corp.

Fig. 451—Left: A flying-spot television camera. Three of the possible five lenses are mounted on the circular scanning disc housing, the desired lens being moved into position by the handle on the outer rim of the housing. The entire camera may be moved vertically by means of the foot pedal on the base. The operator is holding the wheel which tilts the camera vertically.
Right: The interior of a studio from which both sound and television signals are being transmitted. The sound is picked up by the microphone in the foreground. The reflected light from the flying-spot is being picked up by the photoelectric cells in the rectangular metal boxes at the left and right.

tion, through the convenient turret mounting, the scanner can be made to handle close-ups, or half-length and full-length subjects, without moving the relative positions of scanner and subject. The operator stands alongside the scanner which he manipulates during the actual pick-up of a program, following the studio action through a glass window.

When the disc is turned, the light passing through the holes makes successive trips across the subject being televised, so that in one complete turn, every part of the subject has been passed over by a light spot. The subject has been completely scanned. The tiny spot of light that sweeps the subject line by line is reflected in





Courtesy Pilot Radio & Tube Corp

Fig 452—Left: Flying-spot transmission system, and the receiver. The reflected light rays from the pencil of light moving across the subject, act on the photoelectric cells. Right. The arrangement of 4 photoelectric cells in the principal focus of the silvered reflector in back of each one, for increased light pickup, for the arrangement at the left

varying degree, depending on whether it falls on a light or a dark portion of face, body, or clothes. The reflected light is intercepted by a battery of photoelectric cells, generally arranged in two groups placed in front and slightly to each side of the subject as shown at the right of Fig. 451. The photoelectric cells translate the varying light values into corresponding electrical values which, greatly amplified by means of amplifiers placed directly behind the photoelectric cells in the same casing, are sent by wire to the modulator of the transmitter, after passing through the monitoring board. In the control room immediately off the studio and separated from it by glass windows, the control operators follow the pick-up by means of a master radiovisor monitor mounted on the switchboard. Glancing through a peep-hole, the operator sees the television picture exactly as it is being transmitted to the "lookers-in". The degree of gain can be varied so as to provide the necessary brilliancy and contrast in the pictures. Also, by means of the large glass windows looking out into the studio, the control operators can signal the studio announcer about any necessary changes in the placement of subject and equipment. The spots of light sweep over the subject so

rapidly that the eye cannot follow them, and the subject really appears to be illuminated by a steady light.

A schematic diagram of a complete transmitting and receiving system of this type is shown at the left of Fig. 452. The light source behind the scanning disc projects a flying spot or pencil of light on to the subject being televised. The light reflected from this subject acts on the photoelectric cells which are here shown placed in the principal focus of parabolic mirrors for greater collection and concentration of the reflected light rays. A photoelectric cell pick-up assembly of this type is shown at the right. A small photoelectric cell is placed at the principal focus of each of the four silvered parabolic reflectors.

593. Synchronized television and sound transmission: In cases where synchronized sound and television programs are transmitted, the studio also includes one or more microphones suitably placed. A studio of this kind is shown at the right of Fig. 451.

The artist is facing the flying spot beam as well as a microphone which may be just beyond the vision of the pick-up apparatus. Inasmuch as the voice or the music, as the case may be, is picked up simultaneously with the accompanying image, and since electricity and radio waves travel with virtually no delay, the two signals remain in step. There is no synchronizing problem in the radio talkies, or combined sight and sound broadcasting. Of course the combination of sight and sound broadcasting calls for two separate and distinct channels, including separate pick-ups, amplifiers, control room equipment, and transmitting stations, for the present at least. Likewise, two separate and distinct receivers are required at the receiving end, one to pick up the sound signals, and the other to pick up the television signals. When the sound accompaniment is handled by the usual broadcast station, a broadcast receiver may be employed in quite the conventional manner. It is only necessary to know what broadcasting station is handling the sound for a given television station. If the sound accompaniment is through a short-wave transmitter, then, obviously, a short-wave receiver is required.

594. General television tuner and amplifier receiving system: At the receiving station, the incoming television signals must be received, tuned from those of other stations, amplified, demodulated and finally led to a device capable of changing the electric impulses back into correspondingly varying pulses of light. Finally these individual varying pulses of light must be rearranged to form the complete picture.

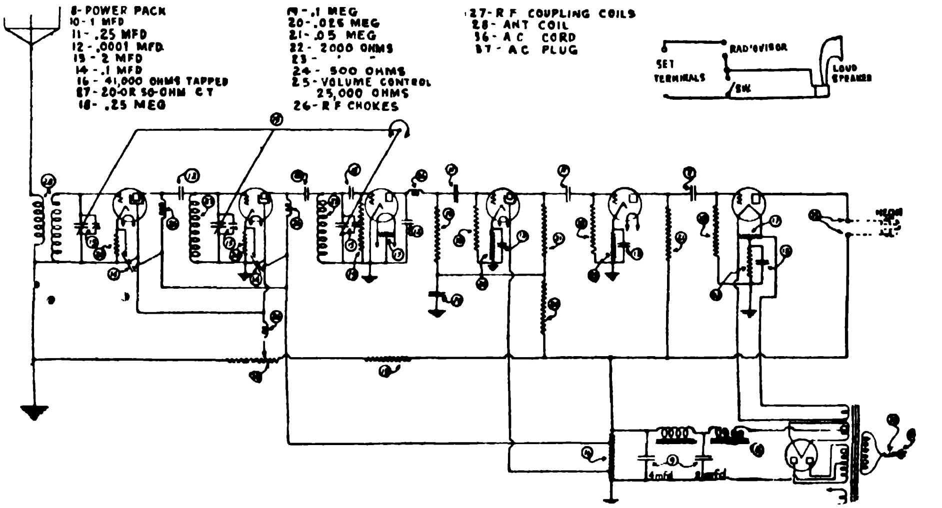
Television transmission is now being conducted with short waves. We found in Article 590 that a wide transmission frequency band is required for present forms of television transmission in which a Nipkow disc is employed. Therefore the television receiver must receive a band of frequencies many thousand cycles wider than the 10 kc band commonly employed in sound broadcasting. This means that the receiver's r-f tuning stages must tune broadly, broad enough to receive about four adjacent broadcast programs at once, if it were used on the broadcast bands. Of course a more selective receiver could be used for television reception, but since the upper sideband frequencies would be suppressed, there would be a sacrifice in the detail of the received picture, when the disc system is used.

The ordinary broadcast band receiver is not suitable for television reception because television transmission is being carried on with short waves from 100 to 150 meters and a short wave receiver is necessary. Even if a short wave adapter or converter is used with the broadcast receiver, reception will not be satisfactory because the audio amplifiers in broadcast band receivers designed for sound programs

only, distort far too much for satisfactory amplification of television signals. Furthermore, the sound which accompanies the television is broadcast on the regular broadcast band; so to get both sight and sound two receivers are required, and the regular broadcast receiver is necessary for the sound reception.

The first requirement of a television receiver then, is that it tune to the carrier frequencies or wavelengths on which the television signals are being broadcast (100 to 150 meters in the U. S.), and that it tune fairly broadly. This means that very little or no regeneration can be employed, since regeneration sharpens the tuning so much that sidebands are cut, and objectionable distortion takes place. The sensitivity must be built up by straight radio-frequency amplification.

The second requisite is to have an audio amplifier that will operate satisfactorily over the required wide range of light-impulse frequencies—



Courtesy The Jenkins Television Corp

Fig. 453—A complete a-c operated short wave television signal receiver consisting of 2 stages of screen grid t-r-f amplification, detector, and 3 stages of resistance coupled audio amplification designed to produce uniform amplification. For listening to the synchronizing signal, the alternate loud speaker connection at the upper right may be employed (See left of Fig. 454.)

up to about 43 kc. The lowest light-impulse frequency is determined by the number of scanning holes passing over the object being televised every second. In a standard 60 line per frame—20 frame per second system, this would be equal to the picture frequency—or 20 cycles. The audio amplifier, therefore, must operate over a range of from about 20 to 36,000 cycles (for a 1×1 inch picture). Resistance coupling offers the only practical form of coupling for an audio amplifier which is to amplify this range of frequencies at all uniformly. (See the amplifier circuit at the right of Fig. 438A.)

If "bias" or plate-current detection is used, it is necessary to employ an "even" number of a-f stages and, since four stages would be too unstable, we must make provision for a higher level of output from the detector tube and drop one a-f stage. The reason is, that in passing through a vacuum tube, the signal is shifted in phase by

180 degrees. This corresponds to a complete reversal of the picture—"maximum" light intensity becoming "minimum"—and a "negative" picture results. The audio-frequency component, therefore, must pass through an even number of such reversals, if a positive picture is to result. In "grid-leak" detection the rectification takes place in the grid circuit and one such displacement occurs before the a-f amplifier is reached. With "bias" or "plate circuit" detection this does not occur and, in consequence, we employ an even number of audio-frequency stages.

The output must be powerful enough to operate the neon lamp used to change the electrical pulsations to light variations. The neon lamp must be large enough to give a clear image. A type '45 output tube or larger has been found satisfactory for home use. The circuit diagram

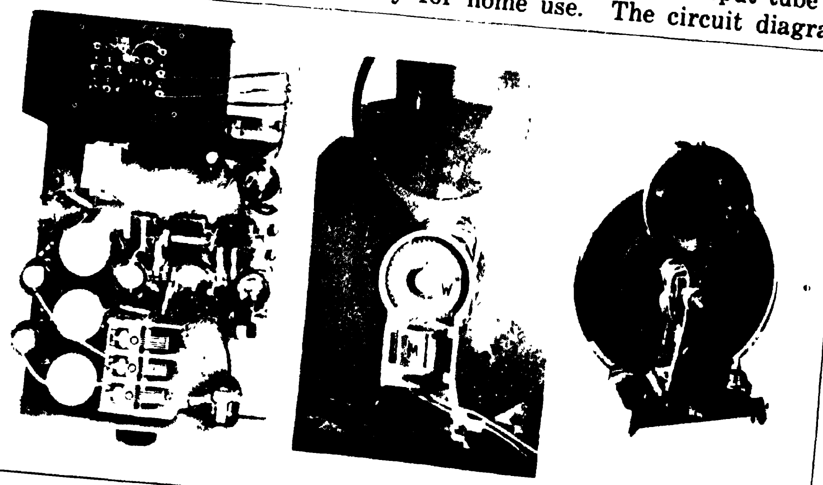


Fig. 454—Left: A top view of the chassis of the receiver whose circuit diagram is shown in Fig 453. *Courtesy The Jenkins Television Corp.*
Center: The "phonic wheel" synchronizer attached to a radiovisor. This depends upon the predominant scanning frequency present in the television signal.
Right: Jenkins stripped televisor with magnifying lens. The driving motor is in the center in front of the disc. The neon tube is just behind the magnifying lens.

of a complete short wave a-c operated television receiver designed especially for the purpose is shown in Fig. 453.

The tuned r-f amplifier consists of two screen grid stages operating with three tuned circuits, using a gang condenser controlled by a single tuning knob. The three tuned circuits serve efficiently to separate the desired station from the unwanted ones, while the two screen-grid r-f tubes provide amplification sufficient to give a good picture signal when the received wave has a field strength as low as 15 microvolts-per-meter. It has been found inadvisable to provide any greater sensitivity than this value, as the background level of static and other electrical disturbances causes distortion to appear in a picture when signals weaker than 15 microvolts-per-meter are received.

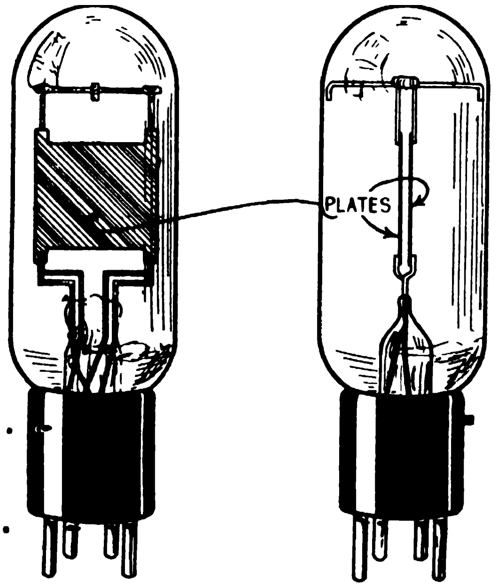
The r-f amplifier, while eliminating unwanted stations, amplifies the side-band frequencies as well as the carrier frequencies, and there is no discrimination which would result in loss of picture detail.

The third unit is a simple grid leak and condenser detector, which separates the latent pictorial values from the signal and passes them along to the audio amplifier for further amplification.

The audio amplifier is resistance-capacity coupled, consisting of three stages. The first tube is a screen-grid type, and the second a standard three-element type,

both being of the separate-heater type. The third stage is an output stage of the '45 type which delivers power to the neon lamp terminals. Thus it is seen that the general circuit arrangement of a television receiver follows standard sound broadcast receiver practice. However, the values of the coupling resistors, blocking condensers, etc., in the audio amplifier have been selected particularly to produce undistorted amplification over the large band of picture element frequencies (these are audio frequencies) to be received. A top view of the chassis of this receiver is shown at the left of Fig. 454. A push-pull output stage may also be used in television receivers.

595. The radiovisor: The television receiver provides the necessary signal output, but not the desired pictures. It may be compared to a sound broadcast receiver without a loudspeaker. A *radiovisor* or



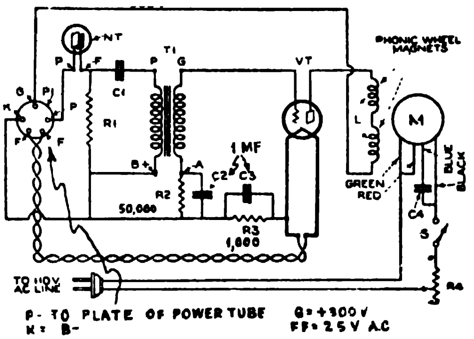


Fig. 455—Left. Front and side views of a neon tube showing the rectangular plates and the gap between them. These connect to the P and the diagonally opposite F prong.

Right: The complete circuit of the synchronization amplifier tube VT and phonic wheel synchronizer magnet coils LL used in the phonic wheel type synchronizer employed in several television receiving systems.

picture-weaving device is necessary. The usual radiovisor comprises a scanning disc, a driving motor, a television neon lamp, perhaps an optical system for enlarging the pictures, and control switches and speed adjustments. A complete radiovisor of this type is shown at the right of Fig. 454.

596. The neon tube: In order to receive television pictures by present methods, there is required a source of light which is capable of changing its brilliancy almost instantly with rapid changes of potential in the receiver. This light reproduces the individual impulses being transmitted, and its position in the circuit is comparable to that of a loud speaker in a broadcast receiver. Up to the present time, the most widely used source of light in radiovisors employing scanning discs, has been the neon tube, although this device leaves much to be desired in the way of an intense light source which will not tire the eyes.

A typical gas-discharge tube of the neon type used in television work is shown at the left of Fig. 455. It consists of two flat metal plate elements insulated and mounted parallel to each other, a small distance apart. The tube is filled with neon gas (the same gas used in the pink glow advertising signs), and may be mounted on a standard 4-prong tube base as shown. One plate connects to the "P" prong and the other connects to the diagonally opposite "F" prong. When a potential difference of sufficient value is applied to the plates the neon gas around the plates become ionized and the plates appear to glow with a pinkish color, the brilliance of the light emitted being proportional to the potential difference between the plates. If a neon tube should be connected to the loud-speaker terminals of a broadcast receiver, it will convert the varying audio-frequency output voltage variations, into corresponding light impulses which are really too fast to be perceived as such by the eye. However, the increase in the light when loud notes are played, is easily seen.

In television, the purpose of the neon tube is to glow with as bright a light as possible but to change its brilliance in accordance with the current through it, or in other words to "modulate" its light as the picture signal is fed to it. The familiar type of incandescent lamp (heated filament) would be entirely unsatisfactory for this purpose as it requires too great a length of time for a change in current to produce a corresponding change in the intensity of the light. The rapid current impulses in television work require that the light-impulse device have no "time-lag." The neon tube meets this requirement perfectly, its light fluctuating rapidly with the incoming signal. It is possible to concentrate the light produced by the neon tube, by adapting a "crater" form for the electrodes. This form has become very popular.

The connection of the neon tube to the output terminals of the television receiver depends upon the type of output tube used in the receiver, and the impedance of the neon tube, for a proper impedance match must be observed for efficient energy transfer and to prevent distortion in the output amplifier tube. In the circuit shown in Fig. 453, the neon tube supplied is designed to be connected directly in the plate circuit of the output tube as shown. If the neon tube has a rather low impedance, say around 1,200 ohms, it should be connected to the output tube by a proper impedance-matching transformer, or by a typical 30 henry choke coil—2 mf. condenser output coupling such as is sometimes employed for loud speakers. Considerable research work is being carried on with light sources of various kinds and it is not at all improbable that an entirely new form of light source will soon be developed to replace the neon tube.

597. The receiver's disc: The neon tube or other television lamp employed, increases and decreases in brilliancy instantly in response to changes in the incoming modulation, growing brighter at the instants when more light reaches the photoelectric cell in the transmitter, and dimmer when the light to the photoelectric cell decreases. In front of the television lamp is a scanning disc *exactly similar* to that used at the transmitter. The observer looks through the rapidly moving holes in the disc, at the neon lamp, as shown at the right of Fig. 450. The transmitting and receiving discs are exactly alike as regards size, shape and layout of the holes. They are driven at exactly the same speed, and are exactly *synchronized*, that is, every hole in one disc is at the same place at each instant as the corresponding hole in the other disc. Each hole in the receiving disc traces a pencil of light *of varying intensity* across the viewing screen. Since these pencils of light traced on the screen, successively one below the other, come so rapidly, the persistence of vision of the observer makes the series of light changes appear to be arranged on the screen in the same order as are the corresponding degrees of illumination on the object being scanned at the transmitter. The rapid changes in the intensity and position of the light-impulses appear to the observer as a picture. If the object moves, the picture at the receiving end appears to move

also. In most radiovisors, a magnifying lens is employed to magnify the size of the image produced, although there is a limit to the amount of magnification which can be employed, due to the fact that the imperfections are magnified just as much as the picture. The radiovisor shown at the right of Fig. 454 shows a magnifying lens in place in front of the scanning disc. This enables a 7 inch picture to be reproduced with this particular equipment.

598. Synchronizing the discs: It is evident that successful television requires the lights and shadows produced at the receiver to be in exact step with the lights and shadows affecting the photoelectric cell or other light-sensitive device at the transmitter. If the scanning disc method is employed, it is essential that the disc at the receiver rotate in synchronism with, and at exactly the same speed as that at the transmitter, so that the pictures will correspond in position on the screen at any instant.

In addition to causing the scanning and receiving discs to operate at the same speed, it is also necessary that any spot scanned on the object be reproduced at the receiver screen at exactly the same instant. If the two discs are not in exact synchronism there will be no picture, or only part of a picture. For instance, if the receiving disc were running at the same speed as the transmitting disc, but was one-half revolution ahead of it, then the picture would have dropped halfway down the screen. Slowing up the receiving disc would make the picture rise on the screen. Speeding up the receiving disc would make the image drop further.

The so-called *synchronous* type of a-c electric motor is used to drive the discs, since it maintains its speed constant with the frequency of the current of the a-c line. Most other types of motors are subject to speed variations when the line voltage changes even so slightly.

In the Jenkins televisor shown in Fig. 454, the driving force for the disc is furnished by a synchronous-type Faraday eddy-current motor comprising four electromagnets acting on a copper disc fastened to the scanning disc which is mounted on a ball-bearing shaft. The details of this are shown in the illustration at the right. Synchronism is obtained by means of a toothed rotor that rotates between a pair of magnets energized by the 60-cycle current. The radiovisor will keep in step only with stations on the same power system. However, due to the close regulation of frequency which is maintained today in most power systems, it is feasible to maintain approximate synchronism on signals from a station outside the power system employed by using a simple manually operated speed control.

Where fully automatic synchronization is desired on signals from stations outside the local power system zone, a simple synchronizing device usually of the *phonic wheel* type is added in some systems. This unit comprises a laminated 60-tooth rotor (for 60 line scanning) which fits on the motor shaft, together with an electromagnet M, fed by the 1200-cycle component filtered out of the intercepted carrier wave. The toothed wheel and electromagnet are shown in the illustration at the center of Fig. 454. The 1200-cycle is a dominant frequency in the common 60-line 20 pictures per second signal ($60 \times 20 = 1200$). The receiver is provided with an additional tube to amplify this 1200-cycle component, which is fed to the magnet windings.

If the speed of the receiving disc is a bit too slow, the pull of the magnets M due to the signal in the output of the extra amplifier tube at the end of each scanning line will pull the disc into step by the action of the magnet poles on the teeth of the toothed wheel W. If, on the other hand, the speed of the disc is inclined to be a bit too fast, the pull of the magnets will act as a magnetic brake which will slow up the speed of the motor sufficiently to keep it in step with the transmitter. A circuit diagram of this simple synchronizing system as used in the Hollis Baird television receivers is shown at the right of Fig. 455. NT is the neon tube in the plate circuit of the receiver output tube, T. is a coupling audio transformer and VT is the amplifier tube for the 1,200 cycle component. M is the motor and L is the phonic wheel magnet.

The number of teeth in the phonic wheel W and the spacing between the poles of the synchronizing magnets is determined by the number of lines being transmitted

per picture. For a 48-line picture, a 48-toothed wheel must be used. For a 60-line picture, a 60-toothed wheel is employed. It will be noted that while the usual 60-cycle current is used to keep the radiovisor approximately in step with the intercepted signal, the 1200-cycle synchronizer adds the necessary acceleration or braking effect so as to complete the synchronization. With this automatic synchronizer, it is claimed to be possible to hold the signals from stations several hundred miles distant in perfect step for an entire evening. Other synchronizing systems have been developed, but lack of space prevents including a description of them here.

599. Operating a disc-type television receiver: To tune in pictures with television receivers of the general type shown in Fig. 453 and 154, the receiver switch is snapped on and its dial is tuned to the desired signals. By means of an external loud-speaker which may be connected to the receiver output by the switching arrangement shown at the upper right of Fig. 453, the characteristic buzz-saw signals of the television transmitter are detected and tuned to loudest volume. The switch is then thrown so that the loudspeaker is replaced by the television lamp of the radiovisor. The motor of the radiovisor is then turned on, and the tiny pink spot of the neon tube as seen through the scanning disc, becomes a line, then a number of lines and finally a glowing screen as the scanning disc gets up to step. The screen then becomes spotted with shadows which are at first meaningless but they gradually weave themselves into pictures as the scanning disc attains the synchronous speed.

600. Various types of scanning discs: There are several commercial variations of the simple scanning disc shown in Fig. 449, all de-

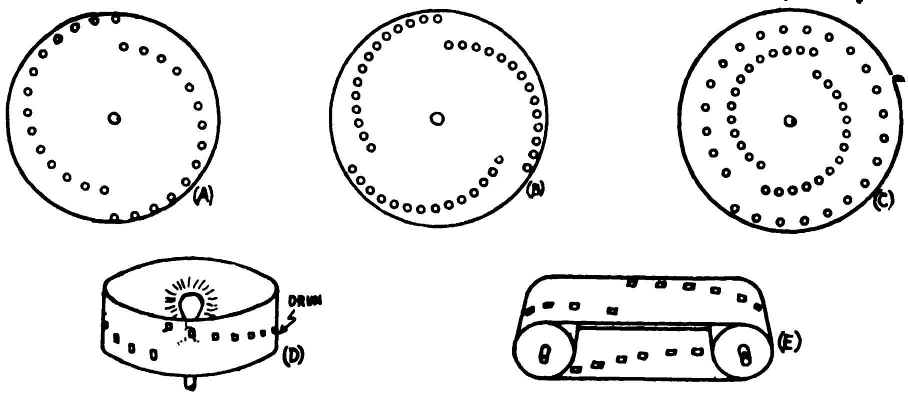


Fig. 456—(A) Flat disc with two sets of scanning holes.
(B) Flat disc with three sets of scanning holes
(C) Single disc with 2 sets of holes arranged to receive signals from stations employing 2 different numbers of lines per picture.
(D) A scanning drum with the holes arranged in spiral form.
(E) A flexible scanning belt.

signed as improvements over this form. It is possible to arrange the holes in two or more spirals as shown in Fig. 456, with a consequent reduction in the speed at which the disc must rotate.

At (A), the disc has two spirals, each of which completely scans the image. A disc of this kind need only rotate at half the speed required for the single-spiral disc. At (B) is a disc with three spirals, which need rotate at but ⅓ the speed of a disc with one spiral. A single disc may operate with either of two numbers of lines per

frame, if built as at (C), with the holes for one number on a single spiral all the way around the disc and holes for a smaller number of lines arranged in two spirals, each extending half way around the disc.

In addition to the flat discs which have been illustrated, others made in the form of a drum with the holes spirally arranged in the circumference and with the source of light at the center, are shown at (D). A drum scanner is used both in the Hollis Baird receiving systems and in some models of the Jenkins system, on account of their compactness. A travelling belt as shown at (E), with holes arranged spirally has also been used for scanning.

Other interesting scanning systems have been developed; notably that developed by Dr. Alexanderson, in which a Karolus or Kerr cell is used to change the plane of polarization of the light beam going through it by means of an electrostatic field produced by very high voltage; that of John L. Baird, which uses a radially slotted disc in combination with a spirally slotted disc and cellular tubes; and that of Jenkins, in which lenses are used in the disc instead of holes, and the direction of the scanning light rays are directed up and down vertically by the action of a prismatic disc. However, in each case the resultant action of scanning is substantially the same as has been described for the simple disc.

601. The mechanical vs. the cathode-ray television systems: The television systems thus far described make use of mechanical parts which are moved for the control of light beams. These parts have weight and therefore have corresponding inertia and momentum which of course limits the speed of the actions in which they take part. Also, in the systems in which scanning discs are employed, the problem of getting sufficient light through the rapidly moving holes in the disc has been a very important one. If the holes are made small so as to obtain good picture detail, the light passing through is very limited. If they are made large to allow more light to pass through, the picture detail diminishes. Also a wide frequency band is required for transmission if good picture detail is required.

Two schools of television are assuming form out of the various lines of experimental work which have been pursued in this art during the last few years. These are, that in which *mechanical scanning* is employed and that employing *electrical scanning*. The scanning disc or drum is the heart of the mechanical system, while the scanning in the electrical system is accomplished by means of the *cathode-ray* tube.

602. The cathode-ray tube: The general form of cathode-ray tube used for oscillographs and in the cathode-ray television system, contains three essential parts; a thin "stream" or "pencil" of electrons travelling at very high velocity, a fluorescent "target" or luminous screen for these electrons to strike against, and some mechanism for "deflecting" the path of the electron pencil in any direction. The illustrations in Figs. 456B and 457 show two common simple forms of this type of tube used in commercial electrical work. The tube shown at (B) of Fig. 458 shows a special form designed by Farnsworth for use in his cathode-ray television system. We will first proceed with a study of the principle of the operation of the general form of cathode-ray tube, shown in Figs. 456A, 456B, and 457.

The unit consists of an elongated glass tube with a flat end as shown, from which all the air has been thoroughly pumped out. At one end is a heated filament or cathode of coated tungsten (C at left of Fig. 456A), which emits a liberal stream of elec-

trons, precisely as electrons are liberated by the hot cathode of the ordinary form of vacuum tube used in radio receivers. Near this cathode is a metal plate P which is maintained at a "positive" potential with respect to the cathode so that it will attract the emitted electrons strongly toward it at high velocity. In the center of this plate is a fine hole as shown. Many of these electrons moving at very high velocity toward the plate, will pass right through this fine hole and continue on their way as a thin pencil of electrons moving at high velocity (a *cathode ray*), down the entire length of the tube. This may be compared to a ray of sunshine entering a room through a small hole in a window shutter.

At the inside of the flattened end S of the tube, is a screen or "target" of fluorescent materials (zinc silicate in the form of the powdered mineral "willemite" is often used, sometimes in combination with calcium tungstate), which shines brightly at the point where the cathode ray or stream of electrons strikes it. Thus, the point where the ray strikes the screen is made visible by a bright spot of light. This is shown in the view at the left of Fig. 456A.

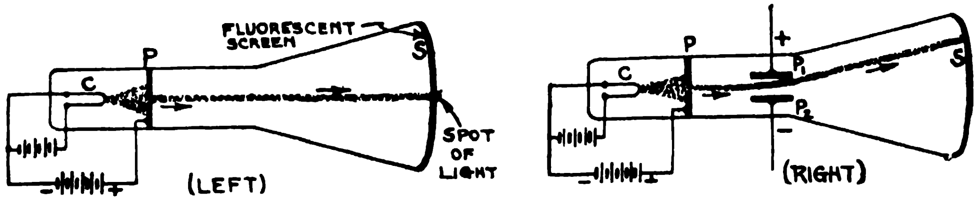


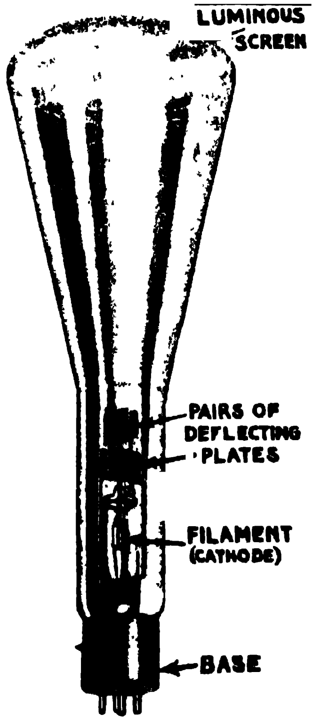
Fig 456A—Left: A simple cathode-ray tube in which the electrons emitted from the heated filament C are attracted by the positive plate P and shot through a hole through its center. They travel to the fluorescent screen S which they strike against and produce light.
Right In this cathode ray tube, two deflecting plates P_1 and P_2 have been added. (See Fig. 456B)

The stream of electrons can be deflected from its straight path by either an *electrostatic* field or a *magnetic* field. If the former method is to be employed, another pair of electrodes in the form of two plates P_1 and P_2 is introduced into the neck of the tube as shown in the view at the right of Fig. 456A, so that the stream of electrons passes through the space between them. If now, any voltage or difference of potential is applied between the plates, so that one is made "positive" with respect to the other, the electrons of the ray, being negative charges, will be drawn toward the positive plate during their passage between the plates. (The electrons are not actually attracted sufficiently to make them actually go to the positive plate.) The result of this deflection is that the electron pencil or stream is bent as shown at (B) so that it strikes the screen at a different spot. If the stream is deflected from the position shown at the left to that at the right by the application of an increasing positive potential on one of the plates, the spot of light will trace a line along the screen. Similarly, a magnetic field applied by a magnet or a coil of wire could be employed to deflect the electron stream. A cathode-ray tube with deflecting coils is shown at the left of Fig. 457. The amount of deflection of the stream and spot of light depends upon the strength of the applied electrostatic or magnetic field. Furthermore, since the electron stream is almost without mass and sluggishness, it can follow even very rapid variations in the applied field. This makes it useful in television work where it is made to move in accordance with the rapid impulses comprising the television signal.

The simple tube shown at the left and right of Fig. 456A provides a means for deflecting the spot of light in one direction or another (depending on which of the plates is made "positive"), along a straight line. By introducing another pair of parallel plates placed at right angles to the first pair, and so that the electron stream can pass between both, as shown clearly in the actual tube illustrated in Fig. 456B, it is possible to deflect the spot of light in a direction at right angles to the deflection produced

by the first pair of plates. Now if suitable individually-varying potentials are applied to both pairs of plates simultaneously, the electron stream may be deflected in any desired direction. The spot of light will travel over the surface of the fluorescent plate, tracing figures of various shapes, depending on the particular variations of these potentials. If one points the lighted bulb of a small pocket flashlight toward his eyes and rapidly moves the flashlight so as to describe various figures, he will have some idea of the movements of the spot of light in the cathode-ray tube.

It is evident, that by applying deflecting impulses of proper frequency and intensity, the spot of light may be made to deflect in any direction across the surface of the screen. For instance one pair of plates can be made to deflect the spot back and forth "across" the screen thus tracing "lines of light," while the other set can be made to alter the position of each line with respect to the next, thus imitating the successive "line" of "strip-scanning" action obtained by means of the common mechanical scanning disc described in Arts. 588 to 592. In this way, images may be traced out by the moving spot of light if proper signal voltages are applied to the two sets of plates. The "lights" and "shadows" in the images thus created, may be produced by properly varying the luminous intensity of the fluorescent spot of light. This luminosity may be controlled by the electron stream density—which may be varied at will by rapidly varying the potential of the plate P having the hole in it, thus varying the attractive force tending to make the electrons move toward the plate. This of course varies the number which reach it, shoot through the hole, and finally reach the screen, to produce light.



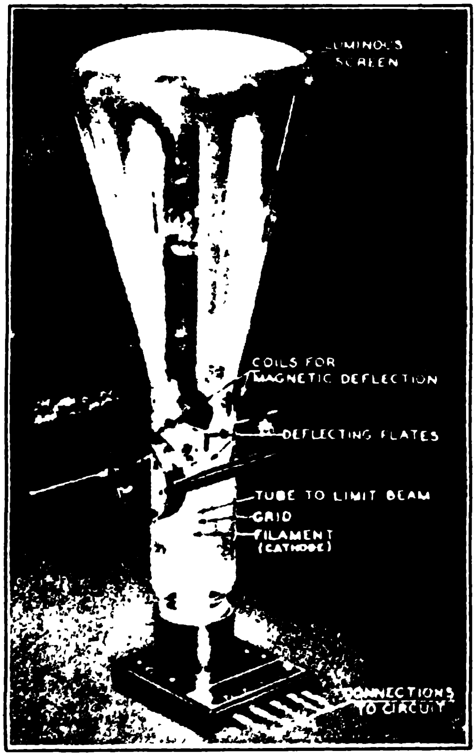
Courtesy Bell Telephone Labs.

Fig. 456B—A cathode ray tube of the form shown in Fig. 456A. This tube has two pairs of deflecting plates. Each pair is mounted at right angles to the others.

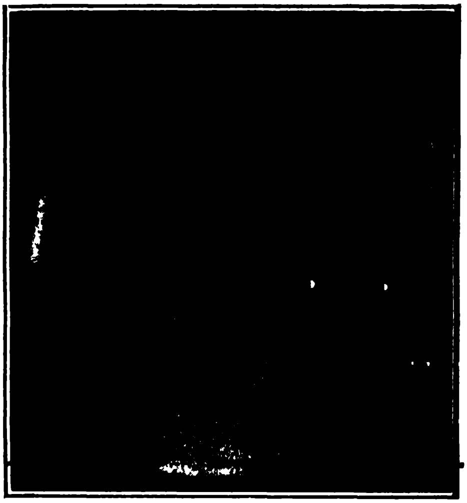
The reader will perhaps realize now why the cathode-ray tube has been looked to as the means for solving the problem of eliminating mechanical scanning discs in the television system. The television signals are applied to the electrodes on the tube in the proper manner so as to cause the correct movement and variation in the brilliance of the spot of light which traces out the images to be received, much the same as a scanning disc does. Of course there are obstacles which must be overcome before this system can be reduced to a practical workable basis. The size of the image is limited to a great extent by the actual practical dimensions of the luminous surface in the tube and the practical amount of deflection of the electron stream which can be produced. Magnifying lenses can be used to magnify the image of course, but there is a limit to this imposed by the fact that the imperfections are also magnified. The "detail" of the image is dependent on

how tiny a spot of bright luminosity can be created on the surface, for this determines the number of "lines" per inch. Another obstacle to be overcome, is the fact that present forms of cathode-ray tubes require rather high plate voltage to produce satisfactory operation and images of sufficient brightness to be seen at a distance in daylight. However, it is hoped that these obstacles will be overcome shortly. While the simple type of cathode-ray tube described here is modified somewhat when used for television, the operating principles involved are similar. A special form of tube construction which has been developed for television work will now be studied.

603. The Farnsworth cathode-ray system: A cathode-ray television system which contains many features which indicate that it may be



Courtesy Bell Telephone Laboratories



Courtesy Radio News Magazine

Fig 457—Left: A cathode-ray tube with deflecting plates inside, and magnetic coils outside to control the movement of the electron pencil as it writes on the luminous screen at the end of the tube.

Right. Unretouched photograph of a television image of 20,000 elements, transmitted by the Farnsworth television system. The screen effect shown here is the result of the half-tone process and did not appear in the original photographic print.

developed into a successful commercial form, has been developed by Mr. Philo J. Farnsworth. In this system, the scene at the transmitter is scanned with a cathode-ray beam, no disks or other moving mechanical parts being used. A cathode-ray beam is also used to re-construct the picture at the receiver. The cathode-ray in the receiving tube and that in the transmitter are kept in exact step by means of a control current

which is transmitted along with the currents which reproduce the moving picture. It is claimed that a 400-line picture can be transmitted in a 10 kc channel by this system. Compare this with the 36 kc channel required for 60-line, 20 picture transmission by the disc scanning method. A reproduction of an unretouched photograph of an image transmitted by means of cathode rays over the Farnsworth system is shown at the right of Fig. 457. The screen effect shown here is the result of the half-tone process and did not appear in the photographic print from which this illustration was made.

The author is indebted to Mr. A. H. Halloran and to the editors of Radio News Magazine for permission to reprint the illustrations and description of a specialized limited case which has been set up to facilitate an explanation of this system. While it does not define the entire procedure of the Farnsworth system, for exact details are not available at this writing, it does give some idea of the system.

A simplified circuit diagram of the system is shown at (A) of Fig. 458. "An optical image of a moving object 5 is focused through a lens 3 on to a silvered mirror

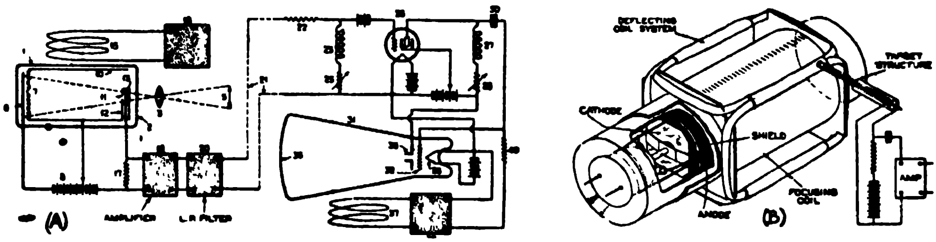


Fig. 458—(A) The simplified schematic layout of the Farnsworth system for narrow-band transmission of moving television pictures. The portion to the left of the dotted connecting lines is the transmitter, while the receiver is to the right.
(B) A perspective view of the "Dissector Tube" employed in this system, showing the design details.

6, this being coated with a material which emits electrons when exposed to light. These parts constitute a sensitive photo-cell of a vacuum type, enclosed in a cylindrical glass tube 1. The mirror 6 is the cathode. Closely adjacent and parallel to it is an anode 7, which is maintained 500-volts positive with reference to 6, by means of a direct-current source 8. The anode consists of a finely-woven wire cloth through whose interstices the liberated electrons are projected into the equi-potential space formed by the shield 10.

Sweeping across the equi-potential space are two electromagnetic fields which are set up by a-c of "saw-tooth" wave-form flowing in two sets of coils placed at right angles around the tube. When one set of coils, diagrammatically represented by 15, is supplied with a 16-cycle current from an oscillator 16, it causes a magnetic field to sweep vertically across the tube 16 times per second. When the other set of coils, which is not shown in the diagram but which can be seen in the perspective view at (B) is supplied with a 3000-cycle current, a magnetic field sweeps horizontally across the tube 3000 times per second. Their resultant effect upon the electrons in the equi-potential space is to form them into a cathode ray image which successively issues from each tiny element of picture area. This cathode ray is then magnetically focused through the small aperture 11 onto the target or electron collector 13.

Hereon is produced a random series of electrical pulses, each having a square front wave $(200)^2 \times 16 \div 2 = 320{,}000$ cycles in width. Each pulse corresponds to an instantaneous change in light intensity in each element of area which is successively scanned by the cathode ray. The variations in light intensity are thus converted

into corresponding variations in current intensity. These current pulses are passed through a 5-stage admittance-neutralized amplifier (18) which is capable of passing a 600-kilocycle wave-band, with a practically straight frequency characteristic.

Neglecting for the moment the filter 20 and the intervening network 21-40, and assuming that a 320-kilocycle distortionless channel were available to transmit the amplified current through the receiver, let us see what happens. The receiver is another cathode-ray tube through which sweep two sets of magnetic fields, one vertically and the other horizontally. The currents to establish these fields are 16-cycle and 3000-cycle "saw-tooth" components of the 320-kilocycle band. Because of their peculiar shape they are readily extracted from among the other frequencies and are used to locally generate or amplify, through oscillators 38, sufficient current to induce the required magnetic fields which cause a cathode ray to sweep across a fluorescent screen 36, thus reproducing a moving picture in exact synchronism with the original moving object 5.

In this vacuum tube, or oscillator, the electron-emitting element is a hot filament 33. The emitted electrons are attracted to and projected through the aperture of a plate 35, the number of projected electrons being controlled by the current pulses on the grid 32. The intensity of these current pulses, it will be remembered, depends upon the intensity of the light which initiates them. Consequently as they emerge from the plate into the space through which the two magnetic fields are sweeping, they are formed into a cathode ray which rapidly scans the area of the fluorescent screen 36, thereby forming the moving picture.

But our assumption of a 320-kilocycle distortionless channel is not justified for either radio or wire transmission. In the entire 960-kilocycle spectrum used by American broadcasters of speech and music, there are only three such channels possible. So the greatest problem in television, and the one which Mr. Farnsworth is probably the first to solve in a practical manner, is how to utilize a narrow channel for the production of a moving picture which has sufficient clearness and detail.

The manner in which he accomplishes this seemingly impossible feat is an interesting story in itself, entirely aside from his remarkable success with the cathode-ray tube. His work is based upon a painstaking study of the Fourier integral theorem, one of the most complex and baffling of all mathematical conceptions. In his study of this theorem he discovered an error and in its correction realized the possibility of suppressing all frequencies beyond the limits of a very narrow band, and then to supply the missing frequencies from derived components of the distorted pulse which is received.

As it would take an accomplished mathematician to understand Mr. Farnsworth's analysis, no attempt will be made to present it here mathematically. Yet it is possible to give an interpretation which can be understood by any student familiar with trigonometry.

Mr. Farnsworth starts with the fact that the abrupt changes in light intensity during the scanning of a picture cause corresponding abrupt changes in the pulses of electric current into which the picture is converted by the scanning process. Each signal wave is characterized by an abrupt square front which suddenly increases from zero to a maximum value, or likewise suddenly decreases from a maximum to zero, in an instant of time. These are the changes that correspond to an instantaneous change from black to white, or vice versa, in a picture. For less intense changes in light intensity, there are less intense changes in current. But always each change is characterized by a vertical wave-front.

But the straight wave-front becomes distorted in the electrical system and also in the transmitter aperture, so that the pulse which arrives at the receiver has a sloping wave-front. It causes a badly blurred picture. Only by filling in the gap of missing frequencies can the oblique front be changed to a vertical front and the blurred picture converted into one whose details are clear and distinct.

This filling-in can be done in various ways. The general idea can be understood by considering one method which happens to be applicable to the wire transmission of a moving picture. This method uses a low-pass filter in the transmitter, as shown at 20. Incidentally it is of interest to know that a band-pass filter, calculated to pass frequencies in the neighborhood of 2100 kilocycles, would enable the pulses to be radiated directly, without the necessity of modulating a separate carrier.

Connected in series with the line is a resistor 22 which feeds a shunt circuit consisting of an inductance 23 and a variable resistor 25. The resistive impedance of 22

is of sufficiently high value to control the current independently of the effect of the inductive impedance 23. The flow of current I through 25 causes a voltage drop e = IR and through inductance 23 a voltage drop e′ which is proportional to the rate of change of current I. It thus becomes the first derivative of I.

The sum of the two voltages e + e′ is impressed upon the grid of a vacuum tube which has a high output resistance. Its plate current, which is an amplification of I and I′, in flowing through resistor 28 causes a voltage drop e″ which is proportional to I and I′. The same currents in inductance 27 cause a voltage drop proportional to their rates of change, thus producing the differentiated currents I′ and I″, which are fed into the condenser 30 which stores or integrates the pulses fed to it, converting part of the second derivative back to the first derivative and part of the first back to the fundamental.

The pulses which are fed to the grid 32 control the intensity of the cathode ray which creates the picture, as already explained. Resistors 25 and 28 are variable, so that the values of the several components can be adjusted until the picture has the best appearance.

It should be remembered that this example merely defines one case of Mr. Farnsworth's invention. His entire idea cannot be fully understood without greater recourse to mathematics than is here possible. But it is hoped that this qualitative analysis of how the warp and woof of the moving picture is first formed by a cathode ray, then cut into a mere scrap of the original, and finally patched so as to reproduce the original pattern, may pave the way for an understanding of the quantitative analysis that will probably be available as soon as the transmitted pictures are ready for reception in the home."

• **604. Future of television:** Present methods for transmission and reception of scenes are by no means perfect. They have very definite limitations, and it is entirely possible that practical television of the future will operate on entirely different principles. The cathode-ray system is practically the only radically new system which has been developed along lines totally different from those already in use. At the time of this writing, the merits of this system have not yet been proved on a commercial basis, and construction and operation data are lacking, only meagre details filtering out from the laboratories in which it is being developed and perfected. Obviously no definite opinions can yet be formed regarding it. It does possess many interesting and unusual features however, and something may come of it.

The circuits and equipment shown in this chapter were included to give the reader an insight into how the television transmission and receiving problem is being attacked and worked out. It is probable that if commercial television ever becomes a practical reality and is perfected to the point where it has entertainment and educational value, the apparatus used may differ in design or even in principle from that described. Although some of the most able scientists in the world are working on the problem, the difficulties involved in making television really practical are tremendous. However, we should not be too pessimistic about the outcome, for in this day of invention and research, the impossibility of yesterday becomes the actual reality of today. Many workers have directed their research to the possibility of transmitting the television programs over the existing telephone or electric light circuit wires in the large cities, rather than attempt to transmit by radio. In this way wide transmission frequency channels could be employed. Just what possibilities this method has to offer still remains to be seen.

REVIEW QUESTIONS

1. What is meant by the term television?
2. What is meant by persistence of vision? How is this utilized in the motion picture; in television? Describe a simple experiment which illustrates persistence of vision.
3. Describe in detail, the principles involved in scanning a scene at the transmitting station by means of a scanning disc. Make all drawings necessary to illustrate your description.
4. Repeat question 3 for the disc in the receiving station.
5. A television system is to be designed to transmit pictures using 48 line—15 frame pictures, 1 inch by 1 inch in size. (a) what must be the speed of rotation of the scanning disc; (b) what audio-frequency range must the receiver handle; (c) draw a sketch showing the layout of the holes on the scanning disc.
6. What is the purpose of the photoelectric cell in television systems?
7. Draw a circuit diagram of a two stage resistance-capacity coupled amplifier for amplifying the output of a photoelectric cell used in a television transmitter.
8. What is the purpose of the neon tube? Explain how it operates.
9. Why are resistance-coupled a-f amplifiers used almost exclusively, in television work?
10. Explain what form of distortion makes a transformer-coupled a-f amplifier unsuited for television work?
11. Why can more distortion be allowed in the a-f amplifiers used in sound amplifier systems, than in television systems?
12. What are the advantages of short wave transmission for television signals?
13. Draw sketches showing three different arrangements of the holes in the scanning discs. What are the advantages of each?
14. State and explain the general advantages which the cathode-ray type of television system has over the type with mechanical scanning discs, etc.
15. State several practical limitations of mechanical scanning disc arrangements.
16. What effect would "static" disturbances due to local electrical interference, thunderstorms, etc., have on the received picture in a television system?
17. Draw the necessary sketches and explain the operation of an ordinary form of cathode-ray tube.
18. Explain in a general way just what purpose a cathode-ray tube can be used to serve in a television system. What are some of its desirable features for this work?

CHAPTER 34

THE ANTENNA AND GROUND

THE ANTENNA SYSTEM — WHY THE ANTENNA IS USED — TYPES OF ANTENNAS — THE RECEIVING ANTENNA INSTALLATION — ANTENNA LENGTH — AERIAL WIRE — ERECTING AND INSULATING THE AERIAL WIRES — THE LEAD-IN WIRE — SHIELDED LEAD-IN — ENTERING THE BUILDING — THE GROUND CONNECTION — THE LIGHTNING ARRESTER — LIGHT SOCKET AND INDOOR ANTENNAS — COUNTERPOISE GROUND — SCREEN ANTENNAS — LOOP ANTENNAS — REVIEW QUESTIONS.

605. The antenna system: Before proceeding with a study of antennas, it would be well to briefly review a few points regarding the terms used in antenna circuit nomenclature.

Considering the usual flat-top types of antennas used for receiving, it has become somewhat common for the layman to use the terms *antenna* and *aerial* interchangeably. Accurately speaking, the top or elevated portion of the antenna is the *aerial*; and that portion which completes the electrical connection between the elevated aerial portion and the receiving instruments, is the *lead-in* wire. The *antenna* is the entire system, consisting of the aerial and lead-in wires. The *ground* really constitutes the earth itself, (or a counterpoise ground system), and the wire connecting the receiving instruments with the earth (see Fig. 177). The latter is sometimes called the *ground wire* or *ground lead.*

606. Why the antenna is used: At the radio transmitting station, the antenna system is used to create the electromagnetic radiations popularly known as "radio waves", which travel out into space. Therefore transmitting antenna systems are designed so that a maximum amount of useful radiation is produced by a given expenditure of electrical power in them. At the receiving station, the function of the antenna system is to act as circuit in which the passing electromagnetic radiations from the transmitting stations may induce signal voltages which are as strong as possible. These signal voltages cause corresponding high-frequency alternating signal currents to flow up and down through the circuit between the aerial wire and the ground, which really form the plates of a large condenser (see Figs. 177 and 179).

The resistance of this path through which the signal current must circulate, should be kept as low as possible so that a maximum amount of current will flow, and act on the receiver circuit. This means that all antenna and ground circuit connections should be well made so as to have as low a resistance as possible. Since the action of the transmitting antenna in producing radiations was explained in detail in Chap-

ter 15, and the action of the receiving antenna was explained in detail in Arts. 243, 244 and 247, this will not be considered again here. The reader is urged to review this work briefly at this time to refresh his memory on these points. It will be remembered that the antenna circuit really forms a condenser circuit.

The arbitrarily selected *standard antenna* which is used in radio receiver sensitivity tests and measurements is an antenna of 4 meters effective height, 25 ohms resistance, 200 micro-microfarads capacitance and 20 microhenries inductance. Such an antenna may be easily constructed artificially for test purposes, (except as to height), by connecting the proper values of inductance, resistance and capacitance together.

607. Types of antennas: Many forms of antennas have been devised for transmitting and receiving, each form having a particular

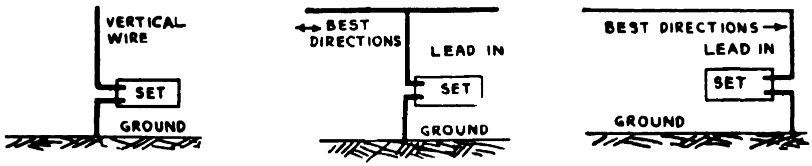


Fig. 460—Left A vertical antenna
Center A T-type antenna with a horizontal top portion.
Right· An inverted L type antenna. This type is used extensively for receiving

characteristic desirable for some special operating condition. Perhaps the most unusual form is the short doublet type with reflectors shown in Fig. 434, and used in the transmission and reception of quasi-optical rays. The more common forms of antennas used for broadcast-band and ordinary short wave transmission and reception will now be considered.

Fig. 460 shows three common simple forms of antennas. At the left is a simple *vertical wire* type, which transmits and receives equally well in all directions. In the center is a *T-type* antenna. This consists of a vertical lead-in wire attached to the horizontal aerial wire at its center point. Antennas of this type transmit or receive best in the line of direction of the horizontal portion, and equally well in both directions along this line. At the right is an *inverted-L* antenna commonly used for reception on account of the convenience of erecting it, as we shall see. It transmits best from the direction of the lead-in end. For ordinary broadcast band reception, it receives slightly better from the direction of the lead-in, but for short wave reception this directional effect is rather marked especially on some frequencies. This property may be taken advantage of for receiving the signals strongly from stations in some particular direction, by properly laying out the receiving antenna's direction.

A *horizontal-V* type antenna is shown at the left of Fig. 461. This is also used quite extensively for receiving. It transmits and receives best in the direction in which the V points. To the right of this is the *umbrella* type antenna. Since this type has a number of conducting paths in parallel, it has a very low resistance, and it transmits equally well in all directions. It is used somewhat for transmitting, but its rather complicated structure has limited its use for receiving.

Two types of *loop* or *coil* antennas are shown next. The one at the left is a *flat* or *pancake* loop consisting of a number of turns of wire wound in the form of a flat spiral coil and supported on a framework (not shown). The *box type* loop has the wires wound in the form of a rectangular box.

The loop type of antenna is commonly used without a ground connection, since it operates entirely by the inductive action of the electromagnetic fields cutting across the wires of the loop, much the same as the action of the armature wires in an electric generator. Loop antennas are constructed from about 1 ft. square, to loops of large size, perhaps to 10 or 15 feet square depending on the space available. Their signal pickup is rather small, and they are used mainly on account of their sharp directional property of transmitting or receiving best from the two directions along the line of the plane of the loop, and practically zero along the line of direction at right angles to this plane. This makes them extremely useful for radio beacon work, (see Art. 539), for electrical interference locators, for radio direction-finding systems, etc.

608. The receiving-antenna installation: Modern radio receivers are being constructed so sensitive, (i.e. provide so much amplification), that in most cases only a very small antenna system consisting perhaps of 10 or 20 feet of wire strung around the picture molding or baseboard of the room in which the receiver is installed, is required for good local-station reception. However, in many locations it is desirable to erect a larger outdoor antenna in which rather strong signal voltages and currents will be set up.

Any attempts to set down definite, detailed rules for the erection of a receiving antenna would be foolish, since the environment of practically every antenna installation presents different conditions which require

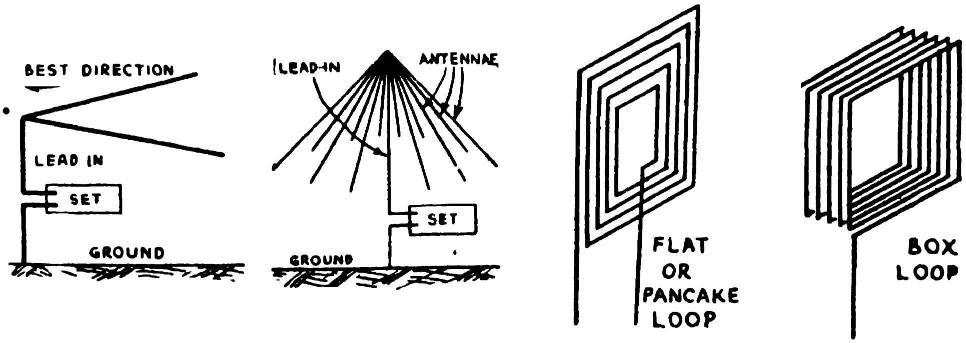


Fig. 461—Left to right; Horizontal V-type, Umbrella type; flat or pancake loop, and box type loop antenna.

that the antenna be designed and erected to conform with them. Thus, it is perfectly easy to specify that an antenna should be erected say 100 feet high and made 100 feet long, but it may not be possible to do this in many installations simply because the surrounding layout of buildings, trees, etc. may not permit it. In crowded locations, such as in city apartment house districts where one encounters countless difficulties in the presence of numerous other antennas, and finds no convenient support for the contemplated one, the best judgment must be exercised. All we

can do is study some of the *general* guiding principles which apply to the installation of antennas in most cases.

609. Antenna length: The amount of energy that reaches the average receiving antenna is too small to be measured directly by any practical instrument. The voltages induced in antenna systems are so small that they are usually measured in microvolts (millionths of a volt) (see Art. 228, 347 and 348). Of course the voltage induced by any one station depends not only on the receiving antenna system but also on the power employed by the transmitting station, its distance away, and the transmission conditions. With modern receivers, excellent reception may be obtained with voltages as low as 100 microvolts (.0001 volts) induced in a good antenna circuit.

If we assume that the average height of an outside aerial is about 30 or 40 feet, a total length of wire not exceeding about 60 to 75 feet is all that is necessary or desirable for ordinary broadcast-band reception. In these days of high-power transmitting stations, an aerial of these dimensions provides ample signal pick up in most cases, and much shorter aerials may very often be used. If the antenna system is made too long, the received energy is greater, but since the antenna picks up the signals of the unwanted stations as well as those of the wanted stations, lengthening it may make the unwanted station signals so strong that it may be difficult to tune them out, i.e., the selectivity decreases. For short wave reception a shorter antenna system having a total length of from about 20 to 40 feet is usually suitable.

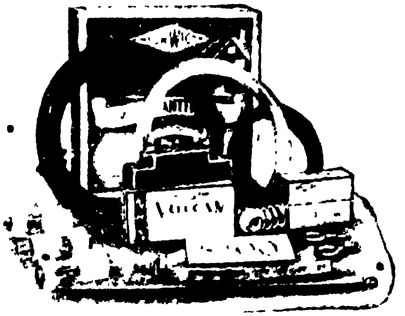
610. Aerial wire: The resistance of the entire antenna and ground system should be kept as low as possible. Number 12 or 14 gauge copper wire is best for *aerial* wire, as it has good conductivity, joints in it can easily be soldered, and it is mechanically strong. Due to some "skin effect", especially at high frequencies, the oscillating currents set up in the antenna circuit may travel along the surface of the wire (see Fig. 291). Therefore, the greatest possible surface should be offered for the flow of current. A wire consisting of 7 twisted strands of No. 22 gauge copper wire offers a larger surface than a single strand of approximately equal cross-section area. For this reason, 7/22 wire, as this stranded wire is called, is used extensively for receiving aerials. It also has great tensile strength. Fancy forms of wire are not necessary. Owing to the rapid oxidation of the wire, which occurs in the smoky atmosphere of cities, the use of *enameled covered* 7/22 wire is often advised but is not really essential. As we shall see, it is very convenient to make the aerial and lead-in of a single piece of wire. Antenna wire is sold in convenient 100-foot rolls for this purpose, (see Fig. 462).

611. Erecting and insulating the aerial wire: The aerial wire should be erected as far away from nearby electric light or power wires as possible.. If it is practical, it should be run in a direction at right angles from such wires, also those of any nearby trolley lines, electric railroads, etc., from which electrical disturbances might be picked up. In

this case the lead-in should be taken off the end of the aerial *furthest* from the source of the disturbance.

The antenna system should also be kept away from large metallic roofs, metal gutters or leaders, steel framework or metal lath of buildings, large trees, etc., since these grounded objects absorb the radio energy and leave little for the antenna. If it is found necessary to run any part of the antenna system over a metal roof, it should be kept at least 8 or 10 feet above it. The aerial wire must be supported at each end. It may be supported by metal or wooden masts, chimneys, trees, etc., but in every case it should be insulated from the supporting objects at each end by suitable insulators, to prevent leakage of the received energy to the earth instead of allowing it to perform its useful function in the radio receiver. If a tree is used as a support, the insulator should be fastened to a wire running to the tree, so that it is kept at least 5 feet from the end of the nearby foliage and branches.

Aerial wire insulators made of Pyrex glass, porcelain, etc., are usually made with an eye or hole at each end for easy fastening of the wire. They are also of ribbed construction in order to increase the length of



Courtesy Cornish Wire Co.

Courtesy Corning Glass Co.

Fig. 462—Left: A complete receiving antenna kit containing all the material necessary for the erection of a complete antenna-ground system.
Right A Pyrex glass antenna insulator. Notice the eye at each end, and the ribbed construction to reduce leakage of the weak signal energy from one end to the other over the surface of the insulator in wet weather

the surface-leakage path from one end to the other. A Pyrex glass insulator of this type is shown at the right of Fig. 462. Notice the eye at each end, and the ribs.

Fig. 463 shows a typical inverted-L antenna installation from a house to a pole erected a short distance away. An additional pole is shown erected on the house (this is not absolutely necessary but helps to elevate the aerial wire). Additional brackets with porcelain knob-type insulators are used to keep the lead-in wire a foot or two away from the side of the building.

The horizontal aerial wire portion is insulated at each end by the insulators shown. It is not necessary or desirable to cut the aerial wire at insulator "A" and join the lead-in wire to it. The lead-in and aerial should both be part of the same single piece of wire. This obviates the necessity for making and soldering a joint at this point. The convenience of this will be appreciated by those readers who have at some time or another tried to keep a soldering iron sufficiently hot until they were able to get to the roof and in position to solder an aerial joint. The detail drawing at the upper right hand corner, shows how the continuous aerial lead-in wire may be fastened to the insulator by a separate fastening wire about 18 inches long. This is drawn through the eye of the insulator to its mid-point; then each end is twisted tightly around the aerial-lead-in wire as shown. The latter wire will not be able to slide or pull out. Due to the changes in temperature at different seasons of the year, the

aerial wire expands and contracts. During the summer it expands, and if it is long it may sag considerably. This expansion and contraction can be taken up automatically by one of the spring-tension aerial wire adjusters made for this purpose. This is usually put between one of the insulators and the guy-wire aerial support. The spring has sufficient tension to just take up the slack in the aerial wire at all times.

612. The lead-in wire: The lead-in wire should be kept at least 6 inches away from all buildings, trees, or other obstructions. It should never be allowed to touch the metal cornice or leader at the edge of the roof, for these are grounded. The lead-in may be kept at a distance of 1 foot or more from the building by means of brackets and "porcelain knob" insulators as shown in Fig. 463. Insulators of this type are

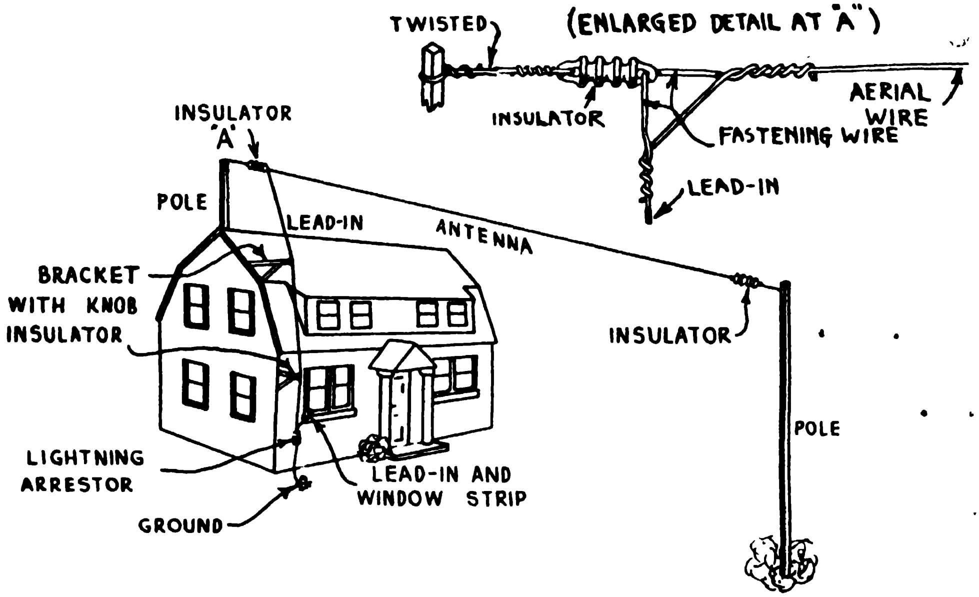


Fig. 463—Installation of a complete inverted-L antenna system on a house. The method of making the continuous aerial lead-in installation at the house end is shown in the detail drawing at the upper right.

shown at the extreme left of the illustration at the left of Fig. 462. Long "stand-off" insulators may also be used for this purpose.

613. Shielded lead-in: In many installations as in apartment houses, hotels, etc., it is necessary to install the aerial wire a considerable distance above or away from the receiver. The long *lead-in* wire of course acts just like the aerial in picking up radio signals, and also in having electrical impulses induced in it by any electrical appliances used in the building. Elevator motors and switching devices, relay contacts on electric refrigerators, etc., may induce considerable disturbing voltages in it, so that reception becomes extremely noisy. In cases of this kind the lead-in wire can consist of *shielded wire*, (see Art. 513).

This may take the form of rubber-insulated copper wire, surrounded by a lead covering or by a braided copper shielding, as shown at (A) of Fig. 464. The outside shielding covering is connected to ground either at lower end, or preferably at several intervals along its length. The wire from the radio receiver to the ground connection may also be shielded in this way if it is long. The aerial wire portion of the antenna system will then be the only part picking up signals and electrical disturbances. Of course shielded wire should not be used for this part, for then no signals would be picked up.

Since the shielded lead-in adds considerable capacitance to the antenna circuit it may throw out the tracking of the antenna tuned stage in a single-dial receiver used with it, and necessitate re-alignment of the first tuning section of the gang condenser in the receiver (see Arts. 632 to 639).

614. Entering the building: Two methods of bringing the lead-in wire into the building are commonly employed. The simplest way is to bring it in through a window nearest to the receiver, using a special flat, flexible, insulated window lead-in strip for this purpose.

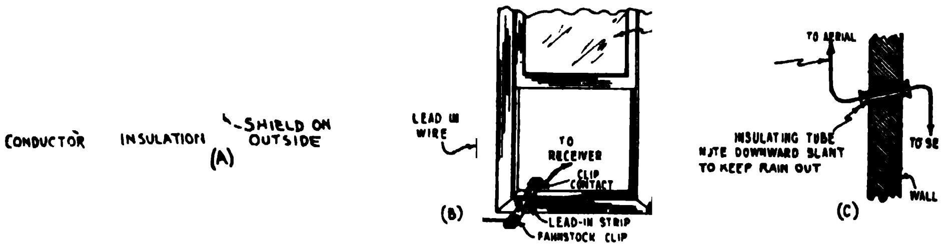


Fig. 464—(A) Shielded lead-in wire used to prevent pickup of electrical disturbances by the lead-in wire.
(B) A window lead-in strip in place between the window and the sill.
(C) A porcelain tube lead-in bushing installed in a wall.

These strips consist of a flat conductor about ½ inch wide, covered with an insulating covering, and provided with a terminal at each end. The strip is placed so the window closes on it, as shown at (B) of Fig. 464, being bent to conform with the shape of window jamb. The end of the lead-in wire connects to the outside terminal, and the wire running to the radio receiver connects to the other terminal. Although clip connections are usually provided on these strips, the wires should be soldered to them, for otherwise they will soon corrode and poor connections result. The strip should have a good waterproof insulating covering. A lead-in strip of this kind is shown directly up front in the left illustration of Fig. 462. A rubber-covered wire of about No. 14 gauge is run from the window lead-in strip to the radio receiver. It may be fastened along the groove or top of the baseboard of the room, with small staples.

In the other method of carrying the lead-in circuit into the building, a hollow porcelain tube bushing similar to the type used in "cleat and tube" electric wiring, is inserted into a hole drilled through the wall, as shown at (C) of Fig. 464. The tube should slope downward to the outside, so that rain running down from the lead-in wire will not run through the tube, into the building. Of course the installation of this tube is very difficult in cases where the wall is made of brick, etc., so the window lead-in strip is more commonly used.

615. The ground connection: The ground connecting wire from the radio receiver to the ground connection should be not smaller than No. 14 gauge. The ground connection should provide an electrical connection of as low a resistance as possible to the earth, since the earth acts as one of the plates of the large condenser formed by the antenna system, and the *full* signal current in the antenna system must flow through the contact during each half cycle. The importance of a good low-resistance contact to the earth cannot be too strongly emphasized. Of course, if a "counterpoise ground" is employed, no "earth" connection is required (see Art. 243).

A water pipe which forms part of a water supply system installed in the earth, usually makes an excellent ground, since it makes intimate contact with the earth for a long distance. Water-pipe grounds are approved by the Board of Fire Underwriters, as they are far more efficient than the average artificial or home-made ground connections. The connection of the ground wire from the receiver, to the

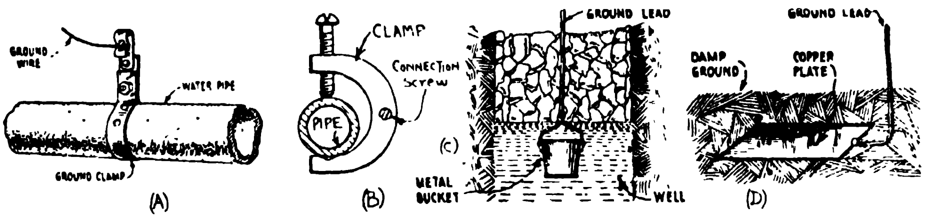


Fig 465—(A) A strap-type ground clamp in place on a water pipe
(B) A C-clamp type ground clamp in place on a water pipe.
(C) Using a metal bucket in a well as a ground
(D) A copper plate at least 2 ft square buried in moist earth makes a good ground.

water pipe should be made by means of a suitable metal "ground clamp" designed especially for the purpose. Merely wrapping the bare wire around the pipe does not make a good ground connection, for the wire will quickly corrode, and a poor contact will result. A ground wire connected to a simple strap-type ground clamp installed on a pipe, is shown at (A) of Fig. 465. In order to make certain of good contact, the pipe should first be cleaned thoroughly by filing off any rust or paint with a file or sandpaper. The strap of the clamp should then be tightened around the pipe. The ground wire should be wound around the screw, and the nut tightened down on the wire. A C-clamp type ground clamp is shown at (B). It is not necessary to clean the pipe first when this is used, since the hardened steel point of the tightening screw and the clamp, bite into the metal of the pipe, and make good contact.

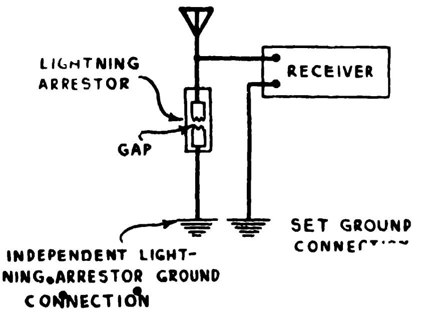
Where a water pipe is not conveniently handy for use as a ground connection, such articles as a radiator, large copper plate or a bucket buried in a well as at (C) of Fig. 465, or a copper plate about 2 feet square buried in moist earth as shown at (D) can be used. Gas pipes should *never* be used for ground connections. A counterpoise ground (see Art. 618) can also be used.

In general, the more well-grounded objects one can connect the ground lead of a receiving set to, the better will be the reception—perhaps not noticeable on local station reception, but certainly noticeable during distant station reception, since the resistance of the antenna-ground path for the signal current is lowered.

616. The lightning arrester: An essential part of any outdoor antenna installation is the so-called *lightning arrester*. The rules of the

Board of Fire Underwriters require that an approved form of lightning arrester always be employed.

The lightning arrester is connected directly from the antenna lead-in wire to the ground, shunting the radio receiver. The lightning arrester in its simplest form as shown at the left of Fig. 466, consists simply of two metal electrodes which are spaced a few thousandths of an inch apart, (either in air or in a vacuum), so that the ordinary low-voltage radio signals cannot jump across this gap to the ground. Therefore, so far as the radio signals are concerned, it presents an *open circuit*, so the signal currents take their usual path from the lead-in wire through the antenna coil of the receiver coil down to the ground. Therefore, the arrester does not affect the radio reception. It takes about 500 volts to break down the air-gap or vacuum-gap in an arrester. However, if high potentials should be induced in the aerial by discharges



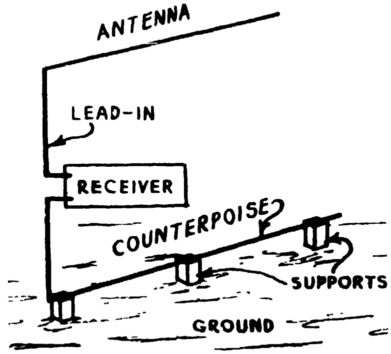


Fig. 466—Left: How a lightning arrester is connected in a receiving system. Right: How a counterpoise ground is installed. The antenna and counterpoise wires form the 2 plates of a large condenser—just as the antenna and earth do in the ordinary antenna-earth system.

of lightning in the vicinity, the voltage is high enough to jump across the small air-gap in the arrester and complete the path directly to the ground, instead of flowing through the larger opposition offered by the inductive action of the primary winding of the antenna-coupling transformer in the receiver. Small sparks may actually be seen jumping across the gap in an arrester on a stormy day. Thus the purpose of the arrester is to drain off the charge on the aerial continuously, to prevent the formation of high potentials. If a direct bolt of lightning should strike the aerial, the intense current flowing through it and the arrester to ground, would in all probability melt the rather fine aerial and lead-in wires. If one thinks for a moment and considers the millions and millions of radio receiving antennas erected all over the world, and how unfrequently any are struck by lightning, all fear of the lightning bogey should vanish. In cities where tall buildings with steel frameworks are erected, there are so many paths offered for the grounding of static discharges that lightning seldom strikes an aerial. In country regions—especially in mountainous localities, the danger from lightning is more serious, since less tall objects are available as paths for the lightning discharges to ground, and low buildings and aerials are often struck.

The lightning arrester is usually enclosed in a porcelain case and may be screwed directly to the outside of the building at the window where the lead-in wire is brought into the building, see Fig. 463. One end should be connected to a ½ inch iron pipe driven at least 3 feet or more into the ground, directly under the window. It is absolutely essential to use this separate outdoor ground for the lightning arrester so as to keep the path of all possible lightning discharges *outside* of the building. The

wire should be fastened to the pipe by an ordinary ground clamp. The copper connecting-wire may be bare, but should be of a size not smaller than 14 gauge wire. It should run in as nearly a straight direct line as possible, to the ground pipe.

617. Light-socket and indoor antennas: In many cases, as in large apartment houses, etc., it may not be practical or desirable to erect an outside antenna for radio reception. An indoor antenna consisting of a single wire laid in the top channel or groove of the picture molding of one or two rooms, or strung up in an attic, is often used as an indoor antenna. Of course the radiations penetrate through the walls of the building and act on the antenna. In buildings in which metal lath is used in the outside walls, radio reception from an indoor antenna of this kind may not be very successful, since the lath acts as a screen and shields the antenna wire from the radio fields.

In some localities, especially where the electric light circuits are distributed on poles in the streets above the ground, excellent results are often obtained with a *light-socket* antenna, consisting of a plug which is screwed into the light socket. Inside the plug is a small fixed condenser, one terminal of which connects to one side of the lighting circuit, and the other terminal of which is brought out to a terminal on the side of the plug, for connection to the antenna terminal in the receiver. The other side of the line is dead-ended. The condenser acts as a blocking condenser to prevent an actual direct circuit for the line current from the line through the set to the ground. It does allow any r-f radio signals picked up by the electric light wires acting as antennas, to act on the receiver, however. Sometimes, better reception is obtained by reversing the plug in the lighting socket. Some receivers are designed for use with a loop antenna concealed inside the cabinet of the receiver.

618. Counterpoise ground: In places where it is difficult to secure a ground connection at all, as in the case of the installation of radio equipment on automobiles or aircraft (see Arts. 243 & 532), or where it is difficult to secure a ground connection of good conductivity (as where the soil is dry and rocky, and the ground water is at a considerable depth), a *counterpoise ground* can be used. This consists usually of a wire, or system of wires, supported a foot or two above the surface of the ground and insulated from it. The counterpoise should run parallel to the antenna and preferably under it. The receiving set is connected to the regular antenna and counterpoise ground as shown at the right of Fig. 466, no connection to the earth being employed.

The counterpoise may consist of several wires, or a wire screen or net. It merely acts as one plate of the antenna-system condenser, with the aerial and lead-in wires as the other plate. As it has good conductivity, it works better than a high-resistance ground even though its surface area is much smaller.

Counterpoise grounds are used extensively where regular ground connections are difficult or impossible to attain. Thus when operating a portable receiver in an automobile, a short antenna can be installed in the roof of the car, and the frame of the car used as a counterpoise ground (see Art. 532). The rubber tires insulate the frame from the earth. Aeroplanes usually use either a trailing-wire antenna or an antenna

mounted on insulated supports above the wings. The wing and fuselage bracing wires, motor frame, etc., are all connected or "bonded" together electrically with wire to form a counterpoise ground.

619. Screen antenna: A simple screen antenna used in some receiver installations, such as on automobiles, in the receiver cabinet in homes in connection with very sensitive receivers, etc., is shown at the left of Fig. 467.

This consists of a copper or brass plate or screen, three or four feet square, which acts as the antenna. A regular ground connection is also used. When a screen of this type is enclosed in the radio receiver cabinet, it has the advantage of making it unnecessary to erect an outside antenna. However, since the energy pickup of the screen is low, a very sensitive receiver must be employed with it.

620. Loop antenna: Loop antennas generally consist of a rectangular or circular coil of from 1 to 15 or 20 turns of insulated wire wound on a supporting framework, as shown at the right of Fig. 461.

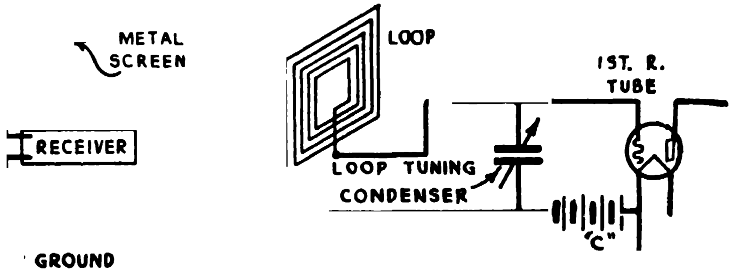


Fig 467—Left: Screen type antenna used extensively in radio installations on automobiles. Right: How a loop antenna may be connected to a receiver; no connection to the earth is necessary. The loop is tuned by the tuning condenser.

•This type of antenna operates solely by the inductive action of the magnetic field sent out by the broadcast station. As this field moving at high velocity cuts across the plane of the loop it induces voltage in the wires by electromagnetic induction. (The action is similar to the induction of voltage in the armature wires of a dynamo.)

If the loop is turned so the field strikes along the direction of its plane, the induced voltage in the various turns are in such directions as to add to each other, thus giving maximum response. The voltage is induced due to the fact that by the time the field has travelled from one side of the loop to the other side, it has advanced through a part of its cycle, and so the phase-relation of the induced voltages in both sides of the loops differ. If the loop is turned so its plane is at right angles to the advancing signal field, the voltages in both halves are equal and opposite in direction and hence cancel each other. In this case, there is no response.

Loop antennas have small pick-up unless made of large, unwieldy size. They are usually operated with very sensitive receivers, such as superheterodynes, etc. The loop is usually conne ted to the first tuning condenser of the receiver for tuning, as shown in Fig. 467. Consequently, the loop should be designed so its inductance will produce resonance over the entire wave band it is desired to receive, when worked with the particular tuning condenser to be used. The directional effects of loop antennas find very important use in radio direction finders and beam compasses. When maximum response from the beacon transmitting station is heard, the plane of the loop is pointing directly to the transmitting antenna.

REVIEW QUESTIONS

1. What is the purpose of the antenna in a radio transmitting station? Explain how it performs this function.
2. What is the purpose of the antenna in a radio receiving station? Explain how it performs this function.
3. Explain and show by means of a sketch, how an elevated antenna and the earth form a condenser. By means of arrows, indicate on this sketch the path of the signal currents in the entire antenna system.
4. Mark the following parts on the above sketch; (a) the aerial; (b) the lead-in; (c) the ground wire; (d) the earth.
5. Upon what factors does the capacitance of the condensers formed by the aerial, lead-in, and earth depend? Explain!
6. Explain in detail how signal voltages and currents are set up in an ordinary inverted-L type antenna.
7. Draw sketches of 4 types of antennas, and explain the construction of each.
8. Draw a sketch and explain step by step, how to erect a horizontal-L antenna, and ground system complete with a lightning arrester. Show the primary winding of the antenna coupling coil in the radio receiver, connected properly in the circuit.
9. Describe the construction, and explain the operation of a lightning arrester. Why doesn't the signal current leak through the arrester to ground just as the static disturbances do?
10. Why are insulators used on antennas? What desirable properties should antenna insulators have? Explain why ribbing the surface increases the resistance to surface-leakage.
11. Explain why a low-resistance ground connection is important for good reception. What steps should be taken to make the ground system of low resistance?
12. What is a counterpoise ground? What are its advantages? Why is it used in automobile radio installations?
13. Describe a common form of lightning arrester, and show how it should be connected to a receiving antenna.
14. What is a loop antenna? Explain its principle of operation.
15. In which direction does a loop antenna receive best? Why?
16. May rubber-covered copper wire be used as aerial wire? Why?
17. What benefits are secured by shielding the antenna lead-in wire?
18. Describe the construction of a light-socket antenna plug. How does this operate?
19. Why is a separate ground required for the lightning arrester? How is this secured?
20. What is the purpose of the ground clamp? Draw a sketch of one, of the strap type. Explain how the pipe should be prepared before the ground clamp is put on the pipe.

CHAPTER 35

TESTING AND SERVICING

NEED FOR TESTING — METHODS OF TESTING FOR OPEN CIRCUITS — TESTING FOR SHORT CIRCUITS — TESTING FOR HIGH RESISTANCE GROUNDS — CHECKING RESISTANCE VALUES — TESTING FILTER AND BY-PASS CONDENSERS — CIRCUIT ANALYSIS AND SIMPLIFIED CONTINUITY CIRCUIT DIAGRAMS — R.M.A. RESISTOR AND WIRE-COLOR CODES — ANALYZING THE CIRCUITS OF A RECEIVER WITH SEPARATE INSTRUMENTS — THE SET ANALYZER METHOD OF DIAGNOSING TROUBLE — COMMERCIAL SET TESTERS OR ANALYZERS — ANALYZING TUNING CIRCUITS — USE OF THE OUTPUT METER IN ALIGNING — THE OSCILLATOR CIRCUIT — SIMPLE TEST OSCILLATORS — COMMERCIAL TEST OSCILLATORS — ALIGNING TUNED STAGES IN T.R.F. RECEIVERS — ALIGNING TUNED STAGES IN SUPERHETERODYNES — REVIEW QUESTIONS.

621. Need for testing: Radio equipment of any kind is, in the final analysis, merely a combination of electron streams, wires, inductances, resistances and capacitances, properly constructed and connected together. It seems almost impossible that so many different circuit combinations could be evolved from just these five elements, but it is true nevertheless. Consider any receiver circuit, no matter how complicated—that of Fig. 453 will do. Study and analyze it carefully. Look at every part, and you will find that it consists of either a resistance, an inductance, a capacitance, or an electronic-stream device (vacuum tube) with connecting wires. It is possible for any of these parts to become inoperative due to one cause or another; just as it is possible for wires to come loose, causing open circuits; or insulation to deteriorate, rub, or chafe, causing short-circuits. Vacuum tubes are liable to become inoperative due to a decrease of electron emission caused by all of the active material on the cathode becoming used up—or the filament may burn out. If the general arrangement of radio circuits is known, and a knowledge of the various methods of testing for opens, shorts, etc., is at hand, it is possible with some little experience, to locate trouble of any kind in radio equipment.

Many troubles may arise in radio receivers, and it is necessary to know not only how to repair the trouble but also to test for and locate it first. This requires some knowledge of the various methods of testing circuits and repairing inoperative parts. It is not necessarily true that a part is *defective* just because it fails to operate. It may have been perfectly designed and constructed, but may have been mechanically strained, overheated, or otherwise abused in service, causing it to become *inoperative.*

Properly speaking, a *defective* part is one which has been designed or constructed incorrectly. We will first consider the various simple tests for locating and determining simple troubles such as open-circuits, short-circuits, etc., by means of individual instruments. Later we will consider the use of instruments arranged conveniently in groups, in the form of service kits and set analyzers for facilitating rapid diagnosing and localizing of troubles. The arrangement and operation of the various instruments in set testers and analyzers can be much more easily understood and intelligently applied, if the fundamental principles of testing with individual instruments are thoroughly mastered first.

While it is not possible to present a thorough course on testing and servicing of radio equipment in the small space available here, we can set down the fundamental principles which will enable the student to understand the basic ideas involved in this work. After all, since all makes of radio equipment employ somewhat different arrangements of parts and special circuit kinks here and there, considerable practical experience in servicing many models and makes of receivers is necessary before anyone can attack servicing problems in an efficient straightforward manner. But the construction of radio equipment has become so interlinked with basic electrical circuits and principles, that no intelligent service work can possibly be carried out on modern radio equipment without a thorough knowledge of the basic principles. While service work is carried on in practice by diagnosing the trouble first, and then localizing it down to the particular inoperative unit by means of continuity tests, etc., for our purpose it will be best to consider the latter tests first, and proceed to simple trouble-diagnosing later. Since all receivers are composed of a combination of the five basic types of parts already referred to, we will begin our study by considering how each of these may be tested separately. It is assumed that the reader is thoroughly familiar with the construction and operation of electrical measuring instruments as described in Chapter 13. This is essential before proceeding with this study.

622. Methods of testing for open circuits: Any circuit which does not form a complete path for the flow of current is called an *open circuit*. Consider (A) of Fig. 468. This shows a simple circuit consisting of a battery and a resistor, R.

Since the resistor, the connecting wires, and the battery form a complete path for the flow of the battery current we have a *closed circuit*. If a current-indicating device—such as an ammeter or milliammeter of proper range depending on the amount of current flowing—were connected in series with the circuit, it would indicate the number of amperes or milliamperes of current flowing. If a voltmeter were connected across the resistor R as shown, it would indicate the "fall of potential" or "voltage drop" across the resistor, i.e., the amount of voltage or electrical pushing force required to cause the electrons or current to flow through the resistor against its opposition or resistance. Now refer to (B) which shows the same resistor and the same battery, but due to some reason, the resistance wire of which the resistor is constructed has broken or become "open" at point X. Evidently, no current can now flow through the resistor, i.e., the circuit is "open". This will be indicated by the fact that the ammeter does not register at all now. However, the voltmeter will now register the full e. m. f. of the battery, since it is now directly across the battery terminals. Suppose the resistor were perfect but a break occurred in one of the connecting wires. Evidently, the same condition of an "open circuit" would result, no current would flow, and the current-indicating meter would read zero.

An inductance coil "L" of any kind, such as the primary or secondary winding of an r-f or a-f transformer, a power transformer, a choke coil, etc., also normally presents a closed circuit to the flow of current, as shown at (C). If the wire breaks or a connection opens, an open circuit results, and the current stops flowing. The current-indicating meter then does not register when connected in series with the circuit.

In the case of a condenser C, as shown at (D), since the dielectric insulates one plate from the other, no current will flow through it if a direct current voltage is

applied, i.e., so far as d-c is concerned, the condenser normally presents an open circuit and the ammeter will not read if the condenser is perfect. (In the case of electrolytic condensers a small "leakage current" would flow through on this test.) If an a-c voltage were applied to the condenser instead, an a-c current would flow in the external circuit between the plates, this current depending on the value of the voltage applied, and the capacitance of the condenser.

A circuit such as that of a resistor, inductance, or wiring, may also be tested for open circuits or continuity by means of a source of voltage such as a small 4½ volt C battery, and a suitable voltmeter—preferably of the high-resistance type. The

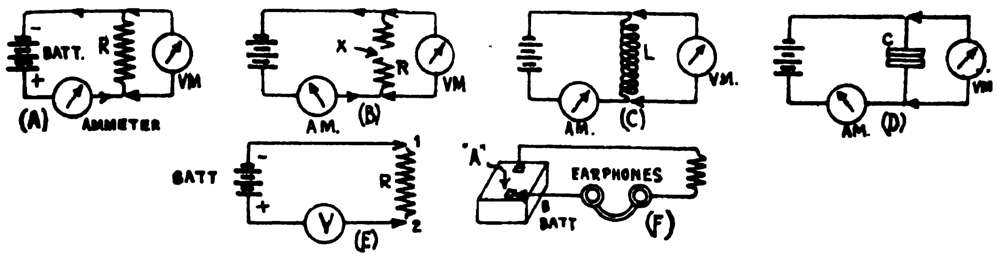


Fig. 468—Various methods of testing for circuit continuity—or "open circuits." (A), (B), (C) and (D) are by means of a battery and meters (E) is by means of a voltmeter and battery, (ohmmeter). (F) is by means of a battery and earphones.

voltmeter, and resistor or inductance winding to be tested for continuity, are connected in series with each other and across the battery as shown at (E). If the two terminals 1 and 2 are touched together, the voltmeter will register the full voltage of the battery. If they are connected across the resistor, the voltmeter will still read if the resistor presents a continuous path for the flow of current. The voltmeter reading may be lower than before, depending on the value of the resistor being tested. If an *open circuit* exists in the resistor being tested, the voltmeter will not indicate.

It will be recognized that the arrangement at (E) really constitutes the ohmmeter circuit which we studied in Article 217. Commercial ohmmeters, one type of which is shown in Fig. 155, are very handy for testing for open circuits. If the circuit is closed, the ohmmeter indicates the resistance of the circuit. If it is "open", the ohmmeter reads "infinite" resistance—or the highest resistance on its scale.

Another simple method of testing for open circuits, without the use of measuring instruments, is to employ a battery—preferably a 45 volt "B" battery—and a pair of earphones as shown at (F). Every time the terminal "A" is *touched to the battery terminal,* a loud click is heard in the earphones if the circuit being tested is "closed". If the circuit is "open", no click at all (or a very faint one), will be heard. When testing condensers, a very faint click will be heard if the condenser is perfect. One disadvantage of this method is that when testing very high resistances for continuity, a very faint click may be heard even if the circuit through the resistor is continuous, since the resistor limits the current through the earphones. This should be remembered.

From the foregoing, it will be seen that any resistor, inductor, or wire circuit may be tested for "continuity of circuit" or "open circuit" by means of a source of voltage and either an ammeter (or milliammeter), a voltmeter, or a pair of earphones. Where two or more devices are connected in parallel and it is desired to test each one for open circuit, they should all be disconnected and each tested separately, for if they were all left connected, even though one had an open circuit it would not show up in the test, for current would still be flowing through the others. If several devices are in series, the test arrangement shown at (B) is handy. When connected successively across each one, the voltmeter will quickly indicate which of the devices is open. It will show a reading equal to the battery voltage when connected across the device which has the open circuit.

623. Testing for short circuits: A *short circuit* may be defined as an accidental low resistance connection between the two sides of a

circuit, such that the current from the source is thereby allowed to return to the source without passing (or only part of it passing) through the device or devices through which it is intended to flow.

Let us refer to the simple circuit at (A) of Fig. 469. This shows a battery supplying current to the filament of a vacuum tube, filament rheostat R being used in the circuit to adjust the current to the proper value for the tube. A voltmeter connected across the filament as shown, indicates the full voltage across it. Now suppose that the two supply wires should for some reason become connected together at some point, as shown at (B). This might be due to the insulation being worn down to the bare wires, or some other cause. It is evident that the current from the source no longer flows through the resistance of the filament, for it can now take a path of less resistance directly across the short-circuit point, and back to the source, as shown by the arrows. This short circuit path is shown by the heavy lines. This represents a *short-circuited condition.* A short circuit will be indicated by the fact that an excessive current flows through the wires from the voltage source, (if the source of the

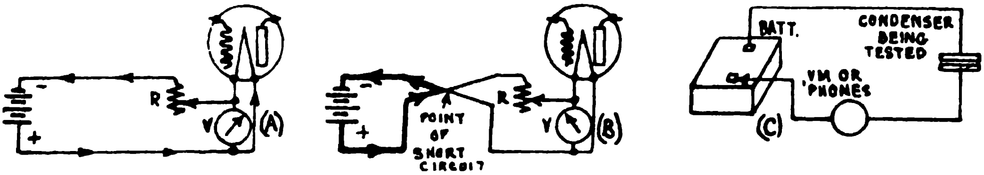


Fig 469—Methods of testing for short circuits. (A), A normal filament circuit. (B), A short circuit in the filament circuit. The heavy lines indicate the path of the current. The voltmeter reading drops to zero. (C) Testing for a short circuit between the plates of a condenser

voltage is able to maintain this heavy current flow), since the resistance of the current path is now very low. Also, a voltmeter connected *across* the device which is intended to receive the current, either reads zero or else reads very much lower than its normal value, since the resistance of the short circuit path is very much less than the normal resistance of the device, and therefore the voltage drop across it is also very low. This may be used as a test for determining short circuits in resistors, inductances or wire circuits.

A short circuit between the plates of a condenser may be determined by connecting it to a source of voltage such as a battery, in series with either a voltmeter or a pair of earphones as shown at (C). If a short circuit exists between the plates, a flow of current across them will be indicated by the deflection of the voltmeter, or by the strong clicks heard in the earphones every time terminal "A" is touched to the battery terminal. If the condenser is O. K., only very faint clicks will be heard, due to the "charging" of the condenser. Of course an ohmmeter may also be used for testing for short circuits, since when it is connected directly across the terminals of the device or circuit to be tested, it will indicate *zero* or at least a low resistance value if a short circuit exists in its dielectric, (see Fig. 155).

When testing for possible short circuits existing in any circuit having several devices connected in parallel, they should first be disconnected from each other and each one tested separately.

624. Testing for high-resistance grounds: In many instances an actual short circuit may not occur between the two sides of a circuit, but instead, a rather high-resistance leakage path, which could not be correctly termed a "short circuit", might occur between them. This is usually called a "high resistance ground", and may be due to deterioration of the insulation between circuits, to abrasion of the insulation, to poor grade of insulating material employed, etc. High-resistance grounds are

probably best tested for by means of an ohmmeter, since then the actual resistance of the leakage path, even if it is high, will be indicated.

625. Checking resistance values: When testing a receiver for defects, it is often necessary and desirable to check the resistance values of the resistors, or other parts. This may be done by the *volt-meter-ammeter method* for low resistances, described in detail in Articles 215 and 216; by the ohmmeter method described in Article 217; or by the Wheatstone bridge method described in Article 218. These methods should be reviewed at this time. Of course, some idea of the resistance which the device to be checked should have, should be known, if its condition is to be judged at all. The ohmmeter method is the quickest and most satisfactory one for radio service work.

626. Testing filter and by-pass condensers: Filter and by-pass condensers used in radio receivers are usually sealed in Bakelite, metal.

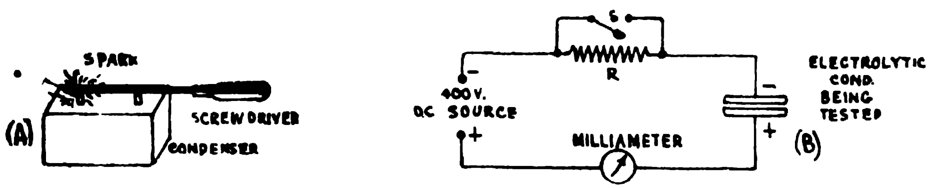


Fig. 470—(A) Testing a condenser for short circuits by charging it with a d-c voltage source and then shorting its terminals.
(B) Testing an electrolytic condenser by measuring its leakage current

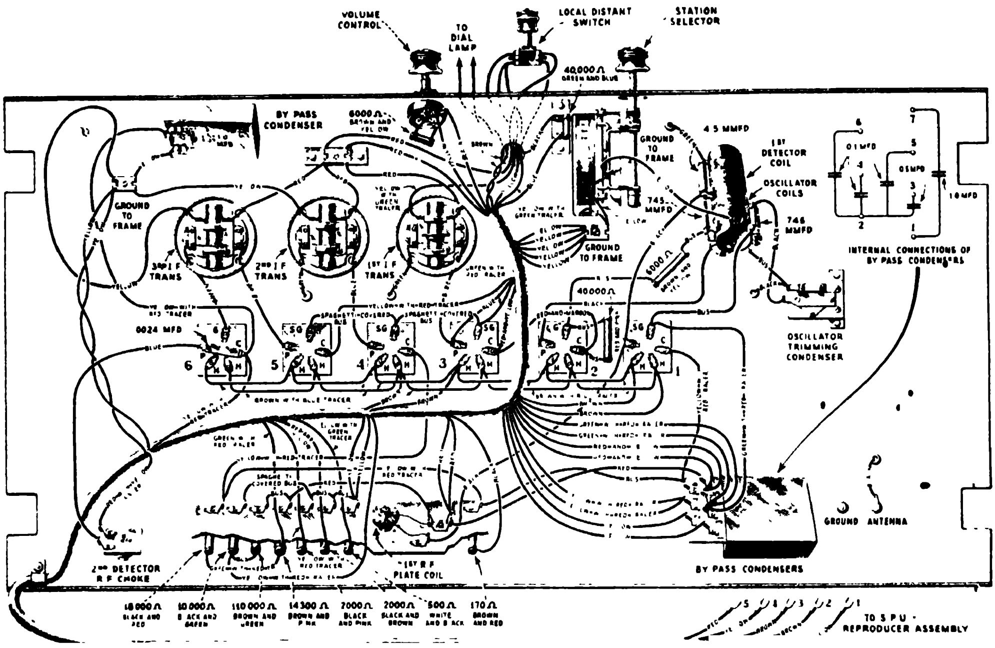
or cardboard containers. The condensers may be in the form of separate units or may be grouped together in one container in the form of a "condenser block" as shown in Fig. 93. In most cases, the condensers in blocks have a common terminal as shown in the diagram in Fig. 93, but in many instances they have separate terminals brought out.

Although open circuits sometimes occur in paper-type condensers due to the metal terminal tab pulling away from the tinfoil plates, this trouble is rare. The usual trouble is due to a short circuit caused by breakdown of the dielectric between the plates. Of course this applies only to condensers of the tinfoil-paper (or mica) type. Electrolytic condensers are "self-healing", that is, if the dielectric film breaks down due to the application of too high a voltage, it re-forms if the high voltage is removed within a reasonable time, and becomes as good as new again.

Tinfoil-paper filter condensers may be tested for breakdown by several methods. One of the simplest, is to disconnect the condenser from the circuit and apply from 90 to 200 volts d-c directly to its terminals, by means of a "B" battery, or d-c electric light line, etc., and then noting whether it holds the charge. Immediately after charging, the charging source is disconnected, and short circuiting the condenser terminals with a screwdriver should produce a flash, the size of the flash depending on the capacitance of the condenser, and the voltage used for charging. This is shown at (A) of Fig. 470. If the condenser has a short circuit between its plates, no charge will be stored by them, and no flash will be produced. This type of condenser may also be tested by means of the

battery and voltmeter or earphone method described for (C) of Fig. 469.

Electrolytic condensers may become inoperative due to drying out of the electrolyte, or chemical changes taking place in it. A condenser of this type may be tested by connecting it directly to a source of d-c voltage (about 400 volts d-c for a condenser rated at 450 volts d-c, and measuring the leakage current flowing through it, by means of a suitable milliammeter as shown at (B) of Fig. 470. Electrolytic condensers of different manufacture differ as to the leakage current, but some idea of the value to be expected may be obtained from the following figures for two typical condensers of this type tested with 400 volts d-c. For a 10-mf. condenser the leakage current did not exceed about 2.4 milliamperes. For a 4-mf. condenser, it did not exceed about 1.0 milliamperes. Care should be taken to connect the condenser to the



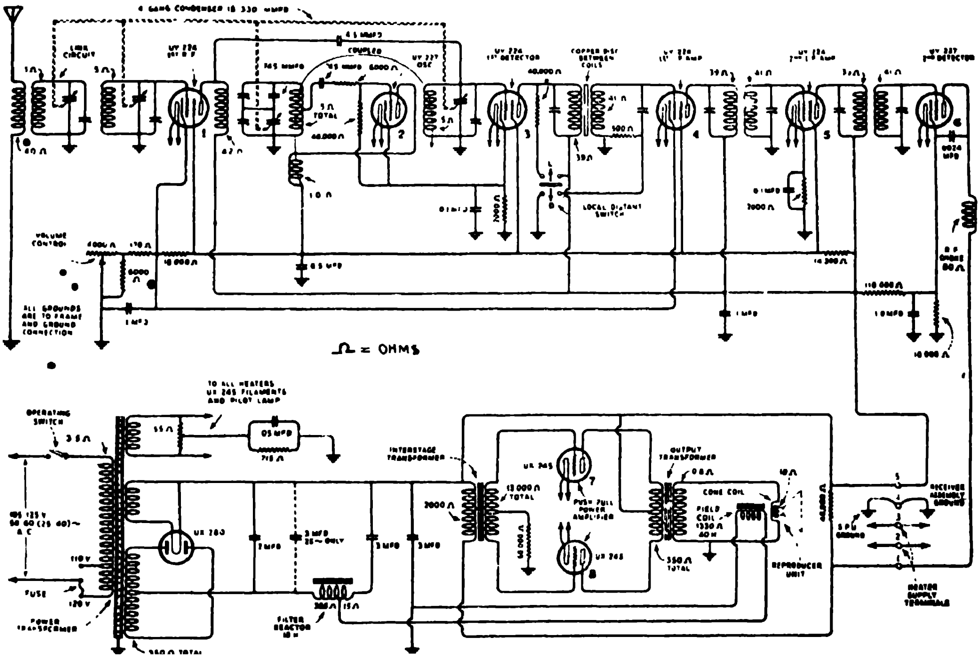
Courtesy R.C.A. Victor Corp.

Fig. 471—How the wiring and parts arrangement under the chassis of a typical radio receiver may look. This appears rather jumbled and complicated, but careful tracing of the various circuits enables one to draw the simple schematic circuit diagram for it as shown in Fig. 472.

line terminals with the proper polarity, i.e., the *positive* terminal of the line should be connected to the *positive* terminal of the electrolytic condenser. Also, to prevent burnout of the milliammeter if the condenser should by chance happen to be short circuited, a protective resistor R, of a value depending on the voltage of the testing source and the range of the milliammeter used, should be connected in series with the circuit at the start, when the voltage is applied. Switch S should be open. If no excessive current reading results, it may be assumed that no short-circuit exists in the condenser and the switch S may be closed. This shorts the protective resistor out of the circuit, and the leakage current reading may now be taken.

627. Circuit analysis and simplified continuity circuit diagrams: In many cases, tests must be made on a radio receiver for which no schematic circuit diagram is readily available, and with which the person who is to test it, is not familiar. By examining the parts and wiring it

is usually a simple matter to determine in general what type of circuit is used in the receiver, i.e., whether it is some form of t-r-f, or a superheterodyne receiver. An inspection of the number of tuned circuits and the number and types of tubes used, will also give some information. Beyond this, nothing may be known about it. If the bottom of the chassis is inspected, a mass of parts and wire somewhat as shown in Fig. 471, may greet the eyes. To the inexperienced novice, such an array appears rather complicated, puzzling, and usually very discouraging. After some practice in tracing circuits however, such things need not be at all troublesome, provided the person has a good working knowledge of the fundamental receiver circuits, such as has been presented in this text. Another



Courtesy R.C.A. Victor Corp.

Fig. 472—The schematic circuit diagram of the receiver shown in Fig. 471 (with the power supply unit added) This is drawn by tracing the individual filament, cathode, grid, and plate circuits of the various tubes and setting them down in the form of a diagram in systematic order Compare the simplicity of this diagram with Fig. 471.

requisite is the ability to take a complicated appearing circuit and part arrangement, trace the main individual filament, cathode, grid, and plate circuits, and set each one down in simplified schematic form on paper, to form a schematic circuit diagram of the type used throughout this book—which is easy to follow, and tells at a glance, just what the individual circuit connections are.

For instance, careful inspection of the receiver chassis, shown in Fig. 471, (the power supply unit is separate and need not be considered here for our purpose), will reveal immediately that there are three intermediate-frequency transformers mounted in shielding cans at the upper left hand corner of the chassis. These are of the general type shown in Fig. 285. This immediately tells us that the receiver employs a superheterodyne circuit. Inspection of the type of power tubes and loud speaker used also tells us something about the possible power supply unit arrangement. Inspection of the tuning condenser tells us how many tuned circuits are used. Inspection of the types of tubes employed and their sequence in the circuit also tells us a great deal about the circuit, and enables us to start drawing our simple schematic circuit diagram by setting down the proper symbols of the tubes in their proper order, as shown in Fig. 472.

We may start with the filament terminals of the tubes, and trace all the filament connections. If they are all connected in the usual parallel arrangement, they can be drawn in the simple schematic form as shown. Next we can trace through the cathode circuits of the tubes, one at a time and draw each one in on the circuit diagram. It will be found that all cathode circuits eventually end up at B—. Next, we can trace the plate circuits, back from the plate terminal of each tube. Next, may come the screen grid circuits and finally, the grid circuits. The power supply unit wiring may be tackled next, or in some cases it may be preferable to finish this first. In this way, a careful step-by-step analysis of the entire receiver may be made, and set down in the form of a simple schematic circuit diagram easy to follow. The complete circuit of the receiver chassis shown in Fig. 471, has been traced in this way and is drawn in simple *schematic* form in Fig. 472, together with the power supply and loud speaker unit which is constructed separately from the chassis of Fig. 471. Notice the simplicity of this diagram and the ease with which any circuit in it may be traced. Most receivers are wired with wires of different colors and code markings to facilitate tracing the circuits. Of course, the resistance values, etc. marked on this diagram, would not be known, but they could be measured if desired. Many of the manufacturers of the R. M. A. group have adopted the standard resistor color code markings for identifying the resistors used in their receivers. The combination of the color marked on the main body of the resistor, that marked on a narrow ring of the body, and that marked on the end, gives the value of the resistance. This is considered in detail in Article 628.

It is true that many commercial receivers are constructed with many of the parts sealed up in groups, in cans which are filled with pitch, wax, or some other moisture-excluding compound, and are therefore not very well adapted to tracing of the connections such as has been outlined here. This condition is one which must be accepted in many cases. Tracing of as much of the circuit wiring as is accessible, will often help some. If more knowledge of the circuit is required, the schematic circuit diagram must be obtained either from the manufacture of the receiver, or from some other source, such as one of the radio service manuals which contain the circuit diagrams for most of the receivers manufactured. One of these books is almost a necessity in service work. In many instances, these service manuals also specify the voltage readings which should be obtained at various points in the circuit when the receiver is in proper working order. This information is very helpful.

628. R. M. A. resistor and wire-color code: The standard resistor color-code marking which has been approved by the Radio Manufacturers Association in the United States, is used on the resistors in the recent models of receivers which are manufactured by companies which are members of this association. It enables one to tell at a glance just what the resistance value of a resistor is, by inspecting the code color markings on it.

The code identifies resistors by means of 3 colors, known as "body," "tip" and "dot" colors. The *Body Color* is the main color of the resistor and represents the first figure of the resistance value. The *Tip Color* is the color of the end of the resistor and represents the second figure of the resistance value. The *Dot Color* (sometimes a narrow

band is used instead of a dot) indicates the number of ciphers following the first two figures.

Example: A resistor has a Red Body—(2); a Green Tip —(5); and an Orange Dot or Band—(000).

Answer: The resistor value is 25,000 ohms.

The figures represented by the various colors are given in the following table:

1st Figure (Body Color)	2nd Figure (Tip Color)	(Dot or narrow Band Color)
0—Black	0—Black	None —Black
1—Brown	1—Brown	0 —Brown
2—Red	2—Red	00 —Red
3—Orange	3—Orange	000 —Orange
4—Yellow	4—Yellow	0000 —Yellow
5—Green	5—Green	00000 —Green
6—Blue	6—Blue	000000—Blue
7—Violet	7—Violet	
8—Gray	8—Gray	
9—White	9—White	

It should be borne in mind that this code applies only to the newer model receivers that are now appearing on the market. It will be a safe practice on all older model receivers to refer to the manufacturer's service notes for the color code used on the earlier model sets.

—WIRE COLOR CODE—

A standard color code has also been approved by the National Electrical Manufacturers Association for the wires used in wiring up the receiver. As is the case with the resistor code markings, this particular wire-marking code is not standard on all receivers, but is being used in the latest receivers manufactured by manufacturer members of the N. E. M. A. The wire color code follows:

For conductors that are individual to one circuit only: "A+," Yellow; "A—," Black with Yellow tracer; "B+" Max., Red; "B+" Int., Maroon and Red; "B+" Det., Maroon; "B—" Black with Red tracer; "C+," Green; "C—(low), Black and Green; "C—" (max.), Black with Green tracer; Loud Speaker (high side), Brown; Loud Speaker (low side), Black with Brown tracer.

629. Analyzing the circuits of a receiver with separate instruments: In testing any receiver for the cause of trouble which may be making it totally inoperative, or else operating unsatisfactorily, a considerable amount of information may be obtained by first testing the individual tubes for either "mutual conductance" or "emission". In many instances, this will reveal one or more of the tubes to have become inoperative, in which case it is only necessary to replace the tube in order to get the set working satisfactorily

If the tubes all check up properly, the voltages which actually exist at their various prongs when they are in place in the receiver, may be checked next with a suitable voltmeter.

This procedure is called *diagnosing* or *analyzing* the receiver, and usually enables one to determine in just which circuit the trouble lies, for trouble occurring in any circuit associated with a tube will usually cause a change in the voltage existing at the tube prong connected to that circuit. After the circuit in which the trouble lies has been located in this ay, the particular unit which is inoperative, may be located definitely by applying the proper separate continuity tests and resistance measurements which we have already studied (in Arts. 622 to 627), to the idividual parts in that particular circuit. Thus, there are really two main steps to radio receiver servicing, first the *diagnosing* or *analyzing*, and then the trouble ***localizing, identification,*** and *correction*.

Each tube has either three, four, or five individual external cir-

cuits, depending on its type. If it is a direct-heater type three-electrode tube, it has a filament, a grid, and a plate circuit. If it is a separate-heater type three-electrode tube, it has a filament, cathode, grid and a plate circuit. If it is a separate-heater type screen grid or pentode tube, it has a filament, cathode, control-grid, plate and screen grid circuit. Keeping this in mind, it is possible to analyze the various circuits of a receiver by testing the voltages existing at these terminals of the tube sockets. In most modern receivers, it is quite difficult to reach directly, the various coupling transformers, resistors, condensers, etc., in order to make tests. In almost all receivers, the main circuits come more or less directly to the tube socket connections, which are easily reached for test work. Therefore a receiver is usually *analyzed* by measuring the voltages existing at the tube socket terminals. In most cases, this will indicate just which of these circuits the trouble lies in.

To illustrate how these circuits may be analyzed, let us consider the typical screen-grid r-f amplifier stage shown at (A) of Fig. 473. The method of analyzing the circuits of this tube and stage may be duplicated for any other stage in the receiver. In the grid circuit of the tube we have the secondary of the preceding r-f transformer with the tuning condenser C_1. In the plate circuit is the primary L of the next r-f transformer, one end of the primary being connected to the plate of the tube, the other end connecting to the plate-filter system consisting of the resistance R_1 and the by-pass condenser C_2. The other end of the resistance R_1 connects to that terminal of the plate supply unit which supplies plate voltage to the r-f amplifier tubes.

Of course, in a complete receiver several tubes comprise the radio-frequency amplifier, but the circuits of each individual tube are closely similar to the one shown here. Slight variations from this fundamental circut will be found, but if this normal arrangement is kept in mind it will make circuit testing a simple task.

In order to check the voltages appearing at the various circuits, individual voltmeters may be used. For a-c electric receivers, two voltmeters are all that are required for this work. One handy instrument for this work is a d-c voltmeter having a resistance of 1,000 ohms or more per volt, (see Article 205), and having scales reading 0-10, 0-250, and 0-750 volts. A meter of this type is shown in Fig. 144. Its scope of utility, because of its high "ohms-per-volt" value, is very wide. As a filament voltmeter for d-c tubes, it affords very accurate readings. As a "B"-supply voltage meter, it indicates the true output, because it does not draw enough current to affect the operation of the power unit. As a grid-bias voltmeter, it permits accurate Adjustment of the grid-bias resistor. Its low current consumption, due to its high resistance, does not materially affect the plate current flowing through the biasing resistor.

An a-c voltmeter of the general type shown at the right of Fig. 144, and having scales reading 0-4, 0-8, and 0-150 volts, is also very useful. The two lower scales are for reading filament voltages on a-c and rectifier tubes, the 150 volt scale is for checking the a-c electric light line voltage. It is possible and desirable to use a single multi-range copper-oxide rectifier type voltmeter for this purpose (see Art. 214), since it will measure both a-c and d-c voltages accurately. The use of separate instruments is considered here merely to develop the methods of testing and analyzing the circuits. Later, we will see how the *set analyzer* performs all of these functions in a rapid simple way.

To check the filament voltage, the a-c voltmeter is connected across filament terminals K-L. To check the plate voltage, the d-c voltmeter is connected between the point H (cathode) and the point F (plate). (*Note*: All voltages or potentials in a direct-heater type tube are always understood to be referred with respect to the *negative terminal of the filament*. All voltages or potentials in a separate-heater type tube are always understood to be referred with respect to the *cathode*, as the reference terminal (see Art. 270). These are considered as the points of lowest potential in the tube.) If the correct voltage reading is obtained between the cathode and the

plate, it indicates that whatever is connected in the plate circuit of the tube (in this case it is the primary winding of a transformer), is not "open". It also indicates that the "B" voltage supply unit is operating satisfactorily. If no voltage reading is obtained between H and F, a test should be made between H and E. If a reading is obtained here, it indicates that an open circuit exists in the primary winding of the transformer. The screen grid circut can be checked by connectng the voltmeter from H to M. The control-grid circuit can be checked by connecting it from H to J. (J is the cap on the tube.) If no reading is obtained here, a test should be made between H and D (D will be usually grounded to the metal chassis). This should indicate the grid-bias voltage if both the grid-bias resistor and its by-pass condenser C_3 are O. K.

This simple test may be repeated at the socket of each tube, until the tube at which the improper voltage exists is located. The individual circuit at which the improper voltage exists can then be traced, and the individual parts in it tested for open or short circuits, etc., by the methods already described. If the plate and grid voltages on all the tubes are found to be low, the circuits of the "B" power supply units may be suspected and should be checked up. Abnormally low output voltage would in all probability be caused by a broken-down filter condenser—necessitating the individual testing of all the filter condensers for shorts.

630. The set analyzer method of diagnosing trouble: The procedure outlined above indicates in a general way how the circuits of each individual tube in a receiver may be analyzed to locate, by means of two simple instruments, the particular circuit in which trouble exists. It has one great drawback in modern test work, however.

When receivers were constructed with all tube sockets mounted on an open baseboard, with every connection easily accessible, this method of testing was simple to

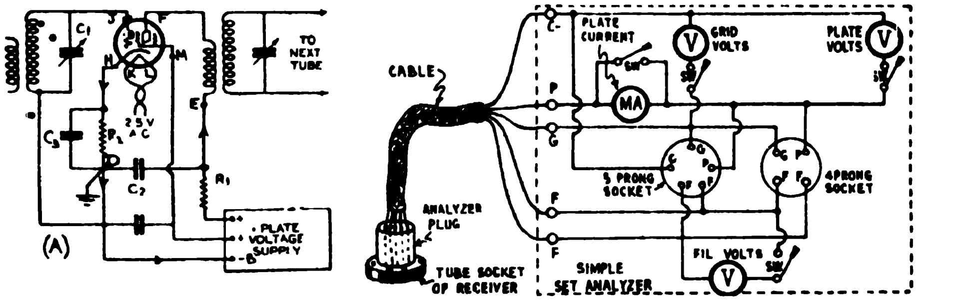


Fig. 473—Left: The individual filament, cathode, control-grid, screen-grid, and plate circuits of a typical screen-grid amplifier tube in a radio receiver. Note that each circuit terminates at the socket and tube.
Right: The elements of a simple set tester or analyzer which permits of rapid testing of the voltages existing at the terminals of any tube socket in the receiver. The analyzer really extends the circuits of the tube socket to a point outside the receiver for convenient testing by means of the various instruments provided. The tube taken from the receiver is plugged into the analyzer tube socket.

apply. Modern receivers are constructed with the tube sockets, resistors, wiring and most condensers, mounted underneath the chassis. Transformers and chokes are mounted in cans. Therefore testing by this method would necessitate the complete removal of the chassis from the cabinet for every service job, and the testing at the tube socket terminals with the set in an inverted position—which is rather awkward, and inconvenient.

The testing manipulations may be greatly facilitated and speeded up, by bringing all of the circuits of the socket of the tube to be tested, to an extra tube socket in which is placed this tube taken from the receiver socket. This extra tube socket is already permanently connected to the testing arrangement, with all meters, switches, etc., arranged to facilitate rapid switching of meters to any circuit, selection of instrument scales, etc. This may be conveniently done by employing a *dummy plug* exactly resembling the base of the vacuum tube, and having prongs arranged in the same order. A wire connects to each prong, and these wires are all brought out,

(usually in the form of a cable), to the similar socket in the tester, in which the tube taken from the receiver is placed. The various instruments and switching arrangements for testing are permanently connected in the tester itself, between the "dummy" plug and this socket.

The arrangement of a very simple set analyzer or tester of this kind in which separate meters are used, is shown at (B) of Fig. 473.

A study of this diagram, shows that the set tester or analyzer idea is merely one designed for convenient testing. Instead of bringing the testing instruments to the terminals on the tube socket, which are usually very inconveniently located—and doing all of the testing in the limited cramped quarters in the receiver; we remove the tube from the receiver socket, extend each individual tube circuit out to the tester by means of the plug and cable, and connect the ends of these extended circuits to the tube taken out of the receiver—the testing instruments being automatically connected properly in between—and do our testing conveniently with plenty of room to work in, and with testing instruments and switching arrangements already connected up in the circuit to perform all the required tests simply and quickly. This is the basis of the set analyzer or tester idea. Of course, in order to make intelligent use of tests of this kind, it is necessary to know just what the voltages at the various terminals of each tube socket should be under normal operating conditions. This data is usually furnished by the receiver manufacturer, or may be obtained from service manuals. Most commercial set analyzers and testers are provided with instruction books containing tables showing the correct voltage readings for most of the standard makes of receivers.

A typical table of this kind for an a-c electric receiver, is reproduced below from the instruction book for the Weston Model 566 Type 2 Radio Set Analyzer. Notice that all the important data concerning the receiver is contained in this table.

MAJESTIC—MODEL 20 CHASSIS

Type Tube	Tube Position	"A" Volts	"B" Volts	"C" Volts	Screen Volts	Screen Current	Cath. Volts	Nor'l MA.	Grid Test MA.
'51	1 R.F.	2.3	180	0	90		3	5	6.2
'51	1 Det.	2.3	180	0	87		8	0.8	1.1
'51	1 I.F.	2.32	150	0	90		3	4.0	5.2
'27	Osc.	2.32	90	0	....	...		4.0	5.1
'27	2 Det.	2.32	255	10			21.6	0.8	1.0
'45	1 A.F. P.P.	2.36	275	45				29.0	33.0
'45	1 A.F. P.P.	2.36	275	45				29.0	33.0
'80	Rect.	4.8	410					40.0	per anode

Line Voltage—117 v. Volume Control set at "Max."

The analyzer is provided with both a 4-prong and a 5-prong socket into which the tube taken from the receiver is placed during the test—depending on its type. Also, the 5-prong plug furnished for plugging into the receiver socket is provided with a removable 4-prong adapter, for use when the circuits leading to a 4-prong tube are to be tested.

Procedure in analyzing: To start the analysis, the set is turned on and the volume control is set at the "MAX" position. The first electrical check should be made on the power supply unit to determine whether it is supplying the normal voltages to the various circuits of the radio set. If the set is of the battery-operated type, check the voltages of the various batteries, with a voltmeter. If the battery voltages are low, they should be re-charged or replaced. (Note: A 45-volt "B" battery unit should be discarded when its voltage drops to about 30-35 volts, measured while it is being used.)

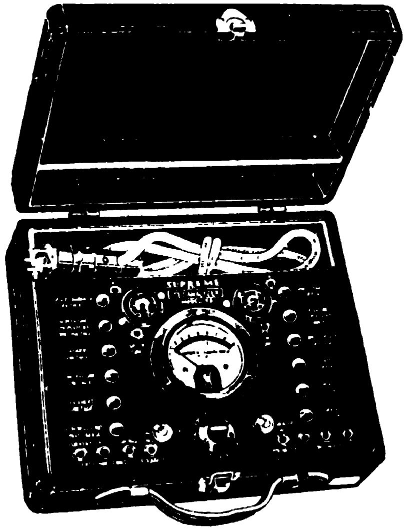
If the receiver is electrically operated, the line voltage should be checked next with a suitable voltmeter. The rectifier tube or tubes should be checked next. The voltages being applied to the rectifier tube plates by the power transformer should be checked next.

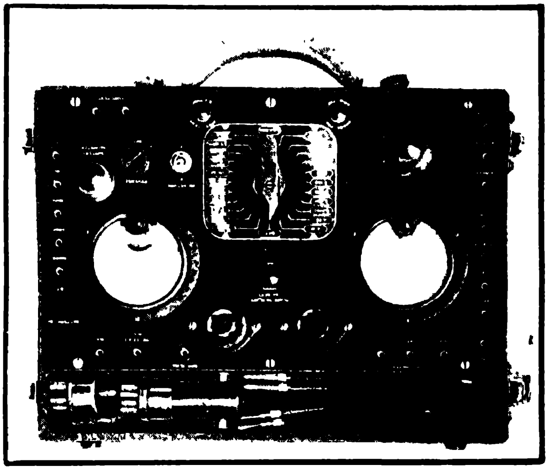
After the source of power to the radio set has been checked in this way, the next procedure is to check the current and voltage supplied to all terminals of each tube in the circuit. The usual practice is to check the tubes in the order in which the signal passes through them, that is, start with the antenna stage and end with the power amplifier or output stage.

Each tube should be removed from its socket in turn, in the above order, placed into the socket of the analyzer, and the plug of the analyzer placed into the same

socket of the receiver from which the tube was removed. By pressing the proper buttons and manipulating the proper switches, as explained in detail in the instruction book accompanying the particular analyzer employed, all of the important voltage and current readings existing at each tube socket may be obtained. The number of readings taken is dependent upon the type of tube used. For a complete analysis of the circuits to a 3-element tube, it is necessary to measure the following values: (1) plate voltage, (2) plate current, (3) grid voltage, (4) grid current, (5) filament voltage. Where cathode, screen grid or pentode tube circuits are being analyzed, the following additional measurements should be known: (6) cathode voltage, (7) screen grid voltage, (8) screen grid current. When making these tests on each tube in the receiver, a rough test of its mutual conductance should also be made by the "grid test method" explained in Art. 290. Set analyzers are provided with a "grid test" button for making this test. These readings may be seen in the last two columns in the table on P. 900.

If this analysis of the voltages existing at the terminals of the tubes shows improper voltages to exist at any terminal, all of the parts in that particular circuit should then be tested for continuity, grounds, short-circuits, etc.





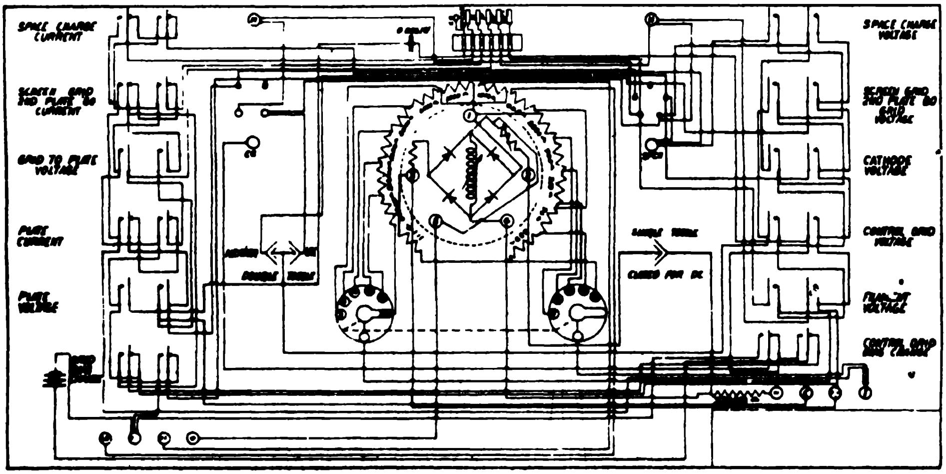
Courtesy Supreme Instruments Corp. *Courtesy Weston Elect. Inst. Co.*

Fig 474—Left: A typical set tester and analyzer arranged in a portable case. A single copper-oxide type meter and suitable switching arrangement performs all tests. The circuit diagram is shown in Fig. 475. The "dummy-plug" and cable are in the compartment at the rear
Right: A typical set tester and analyzer with an a-c meter and a d-c meter. The single selector dial at the center controls the switching arrangement for the entire unit (Weston Model 566 Type 3).

Trouble-localizing: Locating the inoperative part or open connection in a circuit may be accomplished by a simple continuity test, (see Article 622), if the diagnosing process shows the trouble to be due to an open circuit. The simple continuity test is of no value however, when the trouble is due to a short circuit across a device which has a low resistance. In cases of this kind an actual resistance test of each part in the circuit, by low-resistance measuring equipment, is necessary to locate the unit causing the trouble. Of course it is necessary to know the rated resistance value of the unit tested, that is, its ohmic value as specified by the receiver manufacturer. Some manufacturers mark the resistances of the parts directly on the circuit diagrams, as shown in the diagram of Fig. 472. Open circuits are more easily located than short circuits, for the latter do not generally show up in the diagnosis with the set analyzer or voltage test, since they do not materially affect the operating voltages unless the short circuit is *across* the circuit somewhere.

631. Commercial set testers or analyzers: The set analyzer or

test circuits we have considered are extremely simple ones. Modern set analyzers are provided with rather complicated switching arrangements and usually contain but one or two meters to be used for all measurements, both a-c- and d-c. These meters are provided with several multiplier resistors and switching arrangements which enable various ranges to be obtained and enable the operator to switch them to the various circuits to measure the voltages and currents. In addition, suitable terminals are provided for the connection of test prods and leads for making individual tests. These include voltage and current tests, continuity tests, resistance measurements, etc. It is not possible to go into the various circuit arrangements and test procedures to be followed with these instruments here.* Complete instructions are furnished with these testers by



Courtesy Supreme Instruments Corp.

Fig. 475—The complete schematic circuit diagram of the set analyzer shown at the left of Fig. 474. Notice the connections of the single copper-oxide meter, and the multiplier resistors at the center. Also notice the various push-button switches at the left and right for connecting the meter to the various circuits of the tube under test.

the manufacturers in each case. Two typical set testers or analyzers which are representative of these devices are shown in Fig. 474.

The set analyzer at the left employs a single meter of the copper-oxide rectifier type (see Article 214), measuring a-c and d-c voltages in six ranges up to 900 volts, and a-c and d-c currents in five ranges up to 300 milliamperes. It may also be used as an output meter (see Fig. 153) in lining up or adjusting the tuning condenser sections in a gang condenser, and adjusting the tuned circuits in the i-f amplifiers of superheterodynes. Terminals are also provided for making external measurements and tests. The complete circuit diagram of this analyzer is shown in Fig. 475. Notice the connections of the copper-oxide type meter and the multiplier resistor system at the center.

The analyzer shown at the right of Fig. 474 contains two meters—one for a-c and one for d-c measurements. The single selector-dial at the center operates a very ingenious switching arrangement which automatically connects the instruments properly in the tube circuit, for any particular test which may be required. Terminals

*For a more detailed and complete treatise on this phase of the subject, see "The Radio Servicing Course" by Alfred A. Ghirardi & Bertram M. Freed. Published by the Radio & Technical Pub. Co., 45 Astor Place, New York City.

are also provided along the left and right edges for making external tests and measurements. Both analyzers are enclosed in suitable portable carrying cases. Notice that each is provided with both a 4-prong and a 5-prong socket into which the tube from the receiver is inserted. The socket used, depends on whether the tube is of the 4 or 5-prong type. Also notice the cable and 5-prong plug in the rear compartment of the tester on the left. The rear compartment of the tester on the right contains, from left to right, two sets of test wires and prods for external testing of circuits and parts, the 5-prong plug for inserting into the receiver socket, and the 4-prong adapter used when circuits to a 4-prong tube are to be tested. Both of the testers shown, are provided with facilities for testing all of the tubes in the receiver, under the voltage conditions which actually exist in the receiver.

632. Aligning tuning circuits: Both the sensitivity and the selectivity of the present-day single-control t-r-f receiver depends particularly upon how well each individual tuned circuit is in resonance with the others at all positions of the tuning dial. In superheterodyne receivers, it is necessary not only to line up the tuning of the t-r-f and oscillator circuits, but it is also necessary to line up the tuning of the usual band-pass i-f tuned circuits all exactly to the band-pass frequency employed in the receiver. Many receivers do not hold their adjustments; in many, the adjustments must be checked up when new tubes are inserted in the receiver. In either case, it is often necessary to align these tuned circuits so that maximum sensitivity and selectivity are obtained.

One way to align these tuned circuits, is to tune in a distant or weak station, and adjust the *trimming* or *compensating* condensers provided. If the receiver employs tuning condensers with a slotted rotor plate in each section, (as shown in Fig. 268 and 269), the individual segments of the slotted plate must be bent in or out at various positions of the tuning dial, until maximum signal strength results in each case, as judged by the ear. This method is tedious and inaccurate, as the ear is not sensitive enough to be able to distinguish between small changes in intensity of the output sound produced by the receiver (see Arts. 421 and 423) while the adjustment is being made, thus leading to inaccurate adjustment.

633. Use of the output meter in aligning: A more suitable and accurate method of judging the output, is to use an "output meter" of the copper-oxide type (see Article 214 and Fig. 153) for indicating the exact value of the output of the receiver while the aligning is being accomplished. This is very much more accurate than the ear. Some output meters are calibrated directly in volts, others are calibrated in milliwatts. The connections for the output meter will be discussed in Art. 638.

634. Need for the "test oscillator": The tuned circuits in receivers can be aligned by adjusting them while listening to the program from a weak station tuned in, but the use of a special miniature broadcasting station or oscillator for this work permits of much more rapid and accurate adjustments. If the program signal from a broadcasting station is used for this purpose, the *input signal strength* and the *loudness* or *modulation* of the program are very likely to vary while the adjustments are being made, thus leading to incorrect adjustment. When a "test oscillator" is employed for this purpose, the coupling to the receiver, strength of input signal, etc., may easily be adjusted for best conditions, and the frequency is easily adjusted to any particular value desired. A *modulated oscillator* must be used for this purpose.

635. The oscillator circuit: We have already studied how a vacuum tube can be made to produce oscillations of almost any frequency by connecting it in a circuit arranged to continuously feed back some of the energy from the plate circuit (see Arts. 308 and 388).

In an oscillating vacuum tube, part of the varying plate energy is fed back to the grid, inducing an alternating voltage in the grid circuit. This is then amplified by the tube. The limit of amplification is reached when the grid voltage builds up to

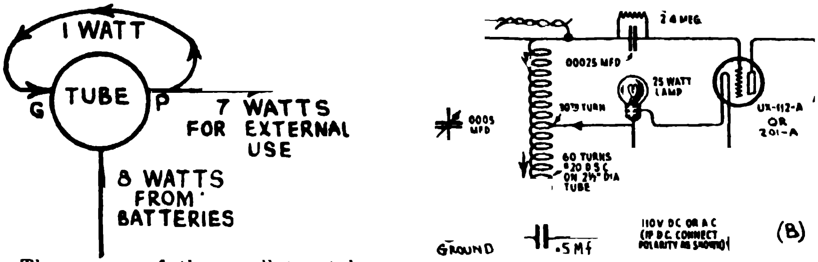


Fig 476—Left: The action of the oscillator tube.
Right: A simple portable test oscillator designed for the broadcast band. It may be operated from either an a-c or d-c volt electric-light circuit

a value large enough to swing over the whole length of the characteristic curve of the tube, for at the ends of the curve any increase in grid voltage has little or no effect in increasing the plate current (see D of Fig. 327).

To consider a case with simple figures, if one watt of energy is all that is required in the grid circuit to make up for the various circuit resistance losses, etc., to work the tube to capacity and to set into motion eight watts of energy in the plate circuit, then by suitably coupling an external circuit to the plate circuit we can absorb seven watts from it for any purpose we desire, and feed one watt back to the grid circuit to be used in sustaining the oscillations. (The extra power comes from the "B" voltage supply device.) This is the principle of the usual oscillator, and is shown in an elementary way at the left of Fig. 476. It is evident that the action of a tube as an oscillator really depends upon the "amplifying properties" of the tube.

There are several common oscillator circuits, each one having certain desirable characteristics which make it suitable for a certain use, all working on the principle of feeding energy back from plate to grid. They are named after the men who first developed them.

636. Simple test oscillators: A simple, portable, self-modulated oscillator circuit which may be operated directly from either a 110 volt a-c or a d-c electric light line, and which is useful in service work for "aligning" the tuned circuits of single-dial control receivers, is shown at the right of Fig. 476.

The coil-winding and tuning condenser data for the construction of a unit of this type for covering the broadcast band from 500 to 1,500 kc is given on the diagram. The arrows show the direction of the plate current. Feedback occurs due to the magnetic field of the part of the coil in the plate circuit linking with that of the part of the coil in the grid circuit. The gridleak and condenser cause the regular blocking action in the grid circuit which modulates the signal, the frequency of the modulation depending on the values of the condenser and leak employed. The entire unit really comprises a regenerative detector operating with sufficient feedback of energy from the plate to the grid circuits to cause oscillation. This oscillator may also be built in battery-operated form by using a separate "A" battery for the filament circuit, and separate "B" battery for the plate circuit. The A+ and B—, or A— and B—, should *not* be connected together. The wire from the terminal marked "A" is an insulated wire twisted together with the insulated wire connected to the tuning circuit, for a distance of 1 or 2 inches. This provides enough capacity to transfer energy from the oscillator to the receiver. A small midget condenser of about 10 mmf. capacity between these two wires will also serve the same purpose, with the advantage

that the coupling may be easily varied. Terminal "A" is to be connected to the "antenna" terminal of the receiver and the "ground" terminal connects to the ground terminal of the receiver. This oscillator could be designed to produce the 175 or 180 kc frequency required for adjusting the band-pass i-f circuits of superheterodynes, by using the proper honeycomb type tuning coils, and tuning condensers of proper capacitance (see honeycomb coil data in Art. 408).

An r-f oscillator, somewhat simpler in general construction, and which will maintain its calibration quite accurately, can be built using the "dynatron" oscillator circuit.

The *dynatron oscillator* uses a screen grid tube operated at such voltages that it is operating at the region below the zero line in the E_p - I_p characteristic curves at the left of Fig. 228. For these values of plate voltages, the secondary emission from the plate (see Article 317 and 318) causes an electron flow in the reverse direction to that normally found in a tube, and oscillations are produced if a tuned circuit is connected in series with the plate, the frequency of these oscillations being determined by the frequency to which the circuit is tuned. Whereas, oscillators using three electrode tubes require coils in both the plate and grid circuits to make them oscillate, the dynatron requires only a single coil. This simplifies the circuit of course, and also makes it easier to use a plug-in coil arrangement for producing oscillations over a wide range of frequencies.

The circuit diagram at the left of Fig. 477 shows a dynatron oscillator arranged to operate directly from the 110 volt line; the voltage may be either a-c or d-c. In the case of d-c voltages, the upper line terminal shown must be the "positive". The necessary potentials for the filament, screen grid and plate (it will be noted in this circuit that the control-grid is tied directly to the filament) are obtained by means of four resistors connected in series across the 110 volt line. Resistance R_4 (50 ohms) serves to reduce the line voltage to about 60 volts for application to the screen grid. R_3 (300 ohms) further reduces the voltage for the plate circuit. R_1 of 1,000 ohms,

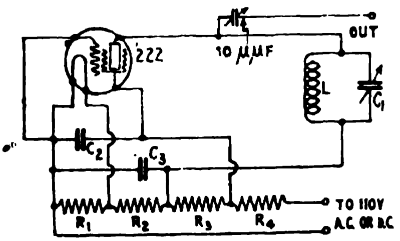


Fig. 477—Left: A simple dynatron oscillator circuit suitable for use as a portable test oscillator. The "constants" of the parts are given in the text.
Right: A dynatron oscillator used in school work for lining up tuning circuits. The tuning coil and condenser are shown mounted on the panel at the left.

and R_2 of 450 ohms, function to supply about 3.3 volts to the filament of the tube. The screen and plate circuits are by-passed to the filament by 1-mf. condensers C_2 and C_3.

If the oscillator is to cover the broadcast band then L and C_1 can be any ordinary coil and condenser designed for use in a broadcast receiver. An old radio-frequency transformer can be used with the primary removed.

When the oscillator is to be used for working on the i-f amplifier of superheterodyne receivers, L can be replaced by a honeycomb coil that will tune to the desired frequency with the condenser C_1. The oscillator can even be used to generate audio frequencies by connecting the primary of an audio transformer in the plate circuit of the tube. By arranging the oscillator to use plug-in coils it will be possible to cover any desired frequency range simply and quickly. If good coils are used the frequency generated by the oscillator will be found to be unusually stable.

637. Commercial test oscillators: A typical complete "modulated" test oscillator with self-contained batteries for its operation, and constructed to be portable, is shown at the left of Fig. 478. The battery compartment is at the left. The oscillator panel and tuning dial are at the center, and the built-in output meter is shown at the right. This makes a complete outfit for checking up the alignment of tuned circuits, for neutralizing receivers, and also for measuring capacity of condensers, inductance of coils, for use as a wavemeter, etc. Its circuit diagram is shown in Fig. 479.

It is completely shielded and has a range from 550 to 1,550 kc for broadcast frequency work, and also a range of 110 to 200 kc for long wave and superheterodyne intermediate-frequency amplifier work.

A positive indication of oscillation is provided by a direct current milliammeter which is normally connected in the grid circuit and serves as a "grid-dip-meter" to

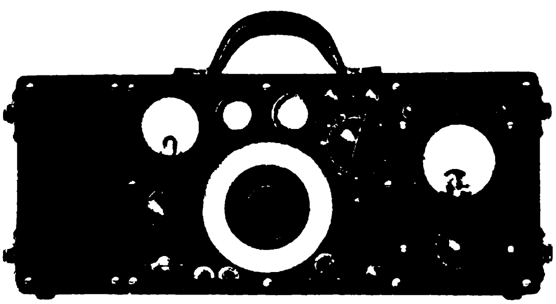


Fig. 478 — Portable modulated battery-operated test oscillator for test work on t-r-f, and superheterodyne receivers, and for tuned circuit aligning. The "grid-dip" resonance indicator is at the upper left; the tuning dial is at the center; an "output meter" is provided at the right. The circuit diagram is shown in Fig. 479. (Weston Model 590.)

Courtesy Weston Elect. Inst. Co

indicate when the condition of resonance has been reached. It also serves as a guide to show when the oscillator is on.

A specially designed attenuator controls the output of the oscillator, which may be varied smoothly and gradually from zero to approximately 5,000 microvolts.

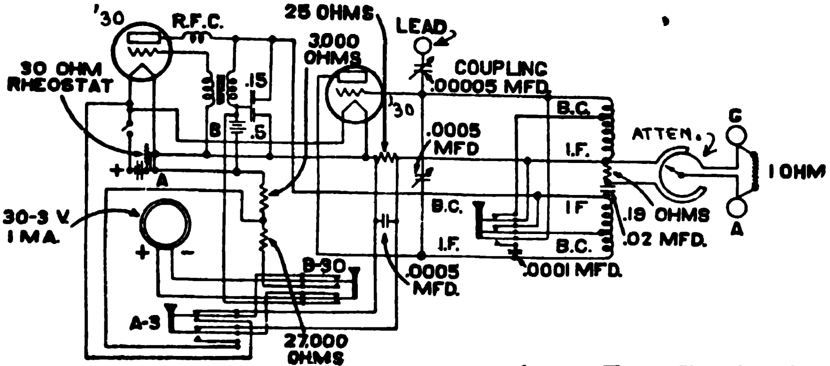
The oscillator uses two '30 type tubes which require a filament current of 60 milliamperes each. With four 1½ V. unit flashlight-type cells, the oscillator will operate satisfactorily for a period of about 20 hours continuously, and much longer when used intermittently.

An external view of another very handy commercial test oscillator is shown at the left of Fig. 480. The metal shield over the oscillator tube is visible directly behind the frequency-adjusting dial. The "signal-strength" or "output control" knob is directly below this. The circuit diagram of this oscillator is shown in Fig. 481.

The oscillator is designed to operate directly from the 110-volt a-c electric light circuit. The r-f signals it produces are automatically modulated *steadily* by the 60-cycle plate-current ripple produced by the a-c power supply employed as the plate voltage source. This modulation causes the output signal of the radio receiver coupled to the oscillator during test, to have an audio-frequency hum corresponding to this modulation frequency. This makes it audible. The grid leak and condenser shown, are not for modulation purposes but are included to provide proper grid-bias for the oscillator tube and to provide protection to the oscillator circuits against possible short-circuits between the grid and plate elements of the oscillator tube. (Notice that the grid-condenser capacity is very large, .02 mf).

A type '30 tube is employed. The tuning unit consists of a 6,200 microhenry inductance coil tuned by a .0005 mf. variable condenser operated by a vernier dial. These

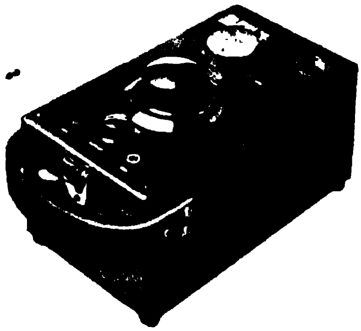
provide a fundamental tuning range of 90 to 250 kc. By utilizing the "harmonic frequencies" generated, the tuning range is spread from 90 to 1500 kc, so the oscillator may be used for aligning the tuned circuits in both r-f and i-f amplifiers. The output signal strength is adjusted by means of potentiometer R_1. This varies the plate

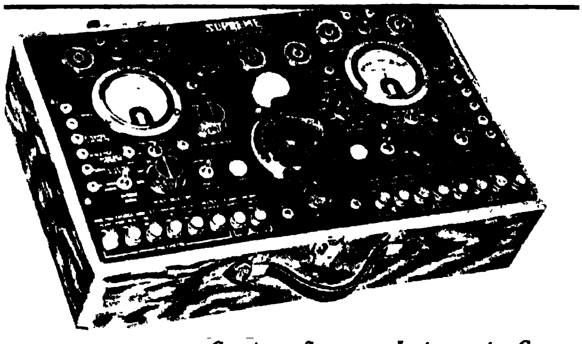


Courtesy Weston Elect. Inst. Co.

Fig. 479—The circuit arrangement employed in the Weston Model 590 test oscillator shown at the left of Fig. 478. A feature of this oscillator is the separate modulator tube at the right. The grid-dip milliammeter provided in the grid circuit of the oscillator to indicate when the tuned circuit being adjusted is tuned exactly to the frequency of the oscillator, is a very helpful feature.

voltage applied to the tube, and so varies the output directly. The full resistance of R· as well as resistance R_2 are always in the circuit in order to reduce the 110 volts of the line down to the 2 volts required for the tube filament. A 6-turn coupling coil L_3 picks up the energy from the tuning coil, and connects to the output circuit. A rather elaborate filter system consisting of two r-f chokes and by-pass condensers





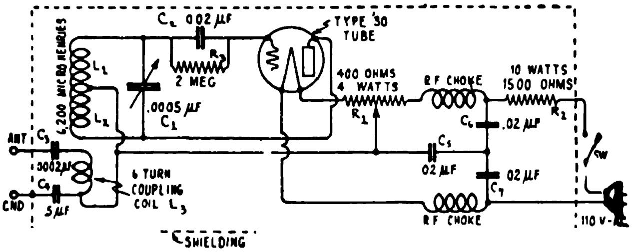
Courtesy Supreme Instruments Corp.

Fig. 480—Left: External view of the a-c operated test oscillator whose circuit diagram is shown in Fig. 481. The entire unit is enclosed in a portable carrying-case. The frequency-adjusting dial is at the center. The leads for connecting to the receiver are not shown here (see Fig. 482 for connections to receiver). (Supreme Model 60)
Right: A complete testing and servicing instrument containing in a single case, a set analyzer, a tube tester, a test oscillator, and an output meter. Simple switching arrangements enable rapid tests to be made. (Model AAA-1 Diagnometer).

C_5, C_6 and C_7 prevent any of the r-f energy from feeding back into the electric light circuit and causing disturbances in radio receivers which may be operating from the same lighting circuit.

At the right of Fig. 480 is a very ingenious combination testing and

servicing instrument of great usefulness. It contains in its single portable carrying-case, a complete set analyzer and tester, a shielded modulated "test oscillator," an output meter, and a tube tester. Thus it contains within its single case, all of the devices required for rapid intelligent servicing of all forms of radio receivers. Its meter ranges permit measurements as high as 1,200 volts to be made, thus making it useful for



Courtesy Supreme Instruments Corp.

Fig. 481—The circuit arrangement employed in the Supreme Model 60 Test Oscillator shown at the left of Fig. 480. The oscillator tube is purposely made to generate strong "harmonic" frequencies which are utilized to give the oscillator the wide frequency-range of 90 to 1500 kc. with a single tuning condenser and set of tuning coils

servicing public-address and sound amplifier equipment. The shielded "test oscillator" is calibrated for every frequency between 90 and 1,500 kc.

638. Aligning the tuned circuits in t-r-f receivers: The use of the modulated r-f test oscillator for adjusting the tuned circuits of a single-dial t-r-f receiver so that each tuned circuit is exactly in "resonance" or "tune" with all of the others at any position of the dial, will now be considered. This proceedure is commonly called, "ganging", "aligning" or "synchronizing". The aligning is usually done by adjusting either the small variable compensating condensers connected in parallel with each of the main tuning condenser sections (see Fig. 100), or else by bending in or out slightly, the fan-shaped segments of the end rotor plate of each condenser section in the gang, when such segments are provided, (see Figs. 268 and 269. Study (B) of Fig. 268).

Type of aligning adjustment provided in receiver: Mention must be made at this point of the fact that the older broadcast receivers do not have slotted end-plates provided for the purpose of condenser alignment. In this case, where only separate compensating condensers are provided for each section of the gang condenser (see Fig. 100), the tuning can be lined up *exactly*, only at one point on the dial. This is usually done at the frequency which the receiver is tuned to, when the tuning dial is set at about 50. In these sets, if the volume or tuning is off at each end of the dial, nothing much can be done about it. If several desired stations that come in at either end of the dial are received poorly, the receiver may be balanced so that these stations are received. Then stations at other points on the dial will come in with less volume.

When a fan-cut rotor plate is provided on each section of the gang tuning condenser, the tuning may be aligned *exactly* over the entire tuning range. The method of adjusting such condensers, is explained in detail at about the middle of Art. 373. This should be studied carefully again at this point. Condensers of this type are shown in Figs. 268 and 269.

The exact procedure to follow for aligning the tuned circuits of a single-dial control t-r-f receiver by means of a modulated r-f test oscillator of any of the types described in Arts. 636 and 637, is as follows: (It is assumed of course that the receiver is in satisfactory operating condition.

(a) Connecting the oscillator: Disconnect the "antenna" wire from the "Ant" terminal on the radio receiver chassis, so that broadcast signals will not interfere with

the signal to be fed to the receiver by the test oscillator. Connect the "Ant." terminal of the test oscillator to the "Ant." terminal on the receiver (or to a special contact point which is in some cases specified by the receiver manufacturer). Connect the "Gnd." terminal of the test oscillator, to the "Gnd." terminal of the receiver. (Most commercial test oscillators are provided with a special shielded lead for these connections, as shown in Fig. 482. In this case, the inside wire connects the "Ant." terminals of both the receiver and test oscillator together. The outside metal shielding (which is insulated from the inside wire), connects the "Gnd." terminals of both the receiver and the test oscillator together. This shield prevents direct radiation of signal energy from the oscillator connecting wire, and makes it all go through the proper channels and tuning circuits of the receiver.) In most cases, the usual "ground" wire should be left connected to the "Gnd." terminal of the receiver or oscillator during the aligning procedure. The entire aligning setup is shown in Fig. 482.

(b) Testing the receiver and test oscillator: To find out whether both the receiver and test oscillator are operating properly, turn on the operating power supply to both the receiver and the test oscillator. Set the oscillator for operation on the broadcast-frequency range. As the radio tubes attain their normal operating temperature, turn the oscillator "output" or "attenuator" control part way up, then set the oscillator tuning-dial at whatever frequency it is desired to start the aligning. Now tune the receiver until the oscillator signal is heard loudest. The volume control of the receiver should be set at "maximum" position. If the signal is too loud, it should be reduced by adjusting the "attenuator" knob on the test oscillator.

(c) Possible ways of connecting the output meter: If it is desired to use an "output meter" (see Fig. 153) to indicate when the receiver has been aligned properly so it produces "maximum" signal output for a given signal input fed to it by the test

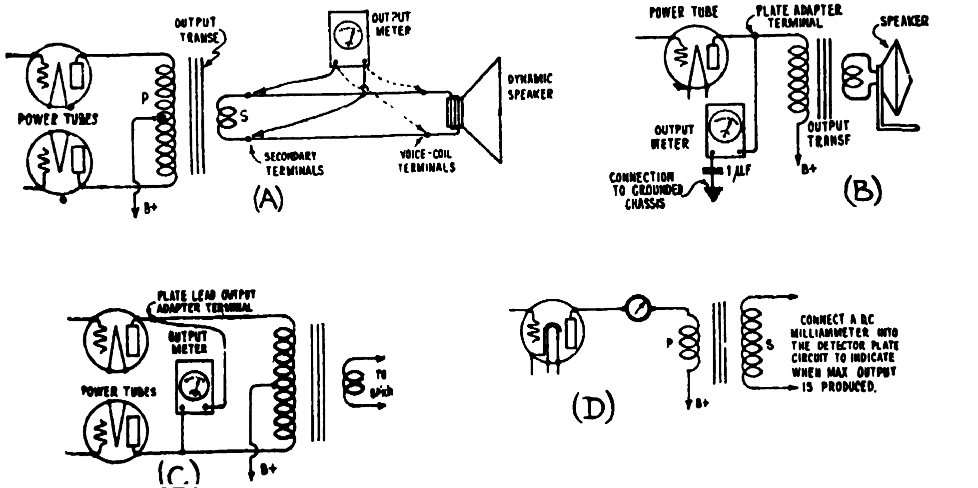


Fig. 481A—(A) The output meter may be connected either across the secondary terminals of the output transformer or across the voice-coil if an electro-dynamic speaker is used in the receiver.
(B) Using a plate-lead output adapter for connecting the output meter across the output if a single power tube is used.
(C) Where push-pull output tubes are used, the output meter may be connected across the plate circuits as shown, by means of plate-lead output adapters.
(D) An 0-5 m.a. d-c milliammeter connected in series with the plate circuit of the detector makes a good output indicator. The indication to be watched for depends on the type of detector employed (see Art. 638 (c)).

oscillator (see Art. 633), turn the power-supply switches "off." The output meter may be connected to the receiver in several ways, depending upon the receiver output stage, and loud speaker arrangements. If the receiver uses an electro-dynamic type of loud speaker, perhaps the most convenient way of connecting the output meter, is directly across the terminals of the voice-coil, or across the secondary terminals of the output transformer, as shown at (A) of Fig. 481A. If these terminals are not easily ac-

cessible, or if a magnetic cone or horn type speaker is employed, the output meter should be connected to the plate circuit of the power output tubes in the receiver.

Here again there are two possible cases—either the receiver uses a single output tube or uses two tubes in push-pull. Also, some of the older battery-operated receivers use an output transformer (or output choke-and-condenser filter), between the plate of the power tube and the speaker terminals. Instead of opening up the connections to these inside the receiver, "plate-lead output adapters" may be employed to break into the plate circuit of the power tube without disturbing any connections. Adapters of this kind are provided with most test oscillators.

In the case of receivers using a single power tube, this tube should first be removed from its socket. The plate-lead output adapter is now inserted over the tube prongs, then the tube is put back into the socket (with the "adapter" in place). The other side of the output meter goes to a 1 mf. condenser, the other side of which should be connected or "clipped on to" the "grounded" chassis of the receiver. The connections of the adapter, output meter, and condenser into the power output tube circuit in this case, are shown at (B) of Fig. 481A.

In the case of receivers employing a push pull output stage, one of these adapters should be inserted in each of the push-pull tube sockets, and the output meter connected to the plate terminals of these adapters as shown at (C).

If a regular output meter (see Fig. 153) is not available, a 0-5 d-c milliammeter connected in the detector plate circuit as shown at (D) may be used instead. If no separate milliammeter is at hand, the milliammeter in a set analyzer may be used for this purpose by inserting the plug of the set analyzer into the detector socket and setting the proper switches to read the detector plate current. If this "plate milliammeter" output indicator is used, with receivers using "grid-bias" or "power" detection, the receiver should be aligned so that *maximum* plate current reading is obtained on the meter. With receivers using "grid leak-condenser" detection, the receiver should be aligned so that *minimum* detector plate current reading is obtained, since in this form of detector the plate current is "reduced" by "increased" signal voltage applied to the grid.

Another simple output indicator, which can be applied to superheterodyne receivers, is a low-range high-resistance voltmeter connected between the "cathode" of the second detector tube and the metal "chassis" (B minus). The readings will be affected by the carrier wave only, and are practically independent of the modulation (since the by-pass condenser across the grid-bias resistor here, smooths out the a-f variations of voltage drop across it).

(d) Aligning the tuned circuits in the t-r-f receiver: After the output meter has been properly connected in one of the ways just described, both the test oscillator and the radio receiver should be turned "ON" and the tubes allowed to warm up for a few minutes. Adjust the output meter range-control for a meter deflection at or below two-thirds of the full-scale deflection. The output meter deflections are arbitrary and are watched merely to find out when "maximum" output is being obtained from the receiver.

With the oscillator operating at a definite frequency—preferably at the high-frequency end of the broadcast-band range—adjust the receiver tuning dial until maximum reading is obtained on the output meter. Now vary whatever adjustments are provided on each section of the gang tuning condenser until maximum output is indicated on the meter. The "attenuator" or "signal strength control" of the test oscillator should be adjusted for less output from the oscillator as the output of the set increases. During the meter indications, the oscillator signals should be audible from the loud speaker. Failure to hear the signals which are indicated by the meter, would be an indication of defective output transformer or loud speaker circuits.

If slotted rotor plate adjustments are provided on the tuning condenser, the adjustment of the segment which is just entering into mesh with the stator plates, should be varied in each condenser section (see Art. 373). In most cases, receiver manufacturers supply information as to the exact frequency at which each segment should be adjusted. Usually these fan-shaped rotor end-plates are made with 5 or 6 segments. One prominent manufacturer uses condenser gangs (see Fig 269), which have each end rotor plate cut into 5 segments, and recommends the following frequencies for adjustment: 1120 kc, 840 kc, 700 kc, 600 kc, and 500 kc. Where no information is at hand, the adjustments should be made at such oscillator frequencies, that *in each case* when the receiver is tuned to the oscillator frequency, the split segment is about

half way in mesh with the stator plates. If receivers possessing this desirable construction feature are aligned carefully, the tuning will be lined up properly over the entire scale or tuning range of the receiver.

(e) **End of the aligning:** After completing the adjustments, turn the radio receiver "off", disconnect the oscillator: re-connect the antenna wire to the "ANT." terminal of the receiver; remove the output adapters (if any have been used) and return the power tubes to their own sockets; disconnect the output meter.

Now turn the radio receiver "on" again and test its ability to bring in stations all over the dial. without oscillation and with sharp tuning. This completes the aligning proceedure.

639. Aligning the tuned stages in superheterodynes: In modern single-dial, superheterodyne receivers, the tuning of the tuned radio-frequency circuits and the oscillator circuits is usually accomplished with a gang tuning condenser. These tuned circuits must be "lined up," but this is usually done after the intermediate-frequency stages have first been aligned.

In these sets, the tuned circuits of the primary and secondary windings of the tuned intermediate transformers (see Fig. 283), must first be aligned at whatever intermediate frequency the receiver is designed for. Intermediate frequencies of 170

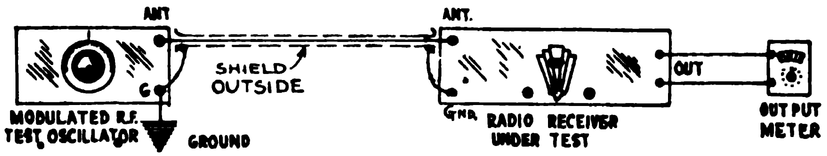


Fig. 482—Test oscillator, radio receiver, and output meter setup for aligning the tuning circuits in a single-control receiver. The oscillator feeds signals of the desired frequency to the receiver. The output meter measures the output of the receiver. The capacity adjustment provided on each section of the gang tuning condenser of the receiver is varied until the output meter indicates that maximum output is being obtained from the receiver. When this is obtained, it indicates that the tuning circuits are properly aligned.

to 180 kc are in common use, although in at least one make of receiver, a frequency as high as 260 kc is used. These stages are adjusted to tune to a definite frequency before leaving the factory, and if for any reason the alignment becomes changed thereafter, the set will not function properly. The general symptoms are, weak reception, broad tuning, and in some cases, poor fidelity. The detailed proceedure to be followed in aligning the intermediate-amplifier tuned circuits will now be considered. It should be remembered that it is not only necessary to align the intermediate stages with each other, but the entire combined i-f amplifier must be tuned accurately to the particular intermediate frequency for which it was designed.

Aligning the intermediate-frequency stages: (a) The oscillator tube in the *receiver* should be removed from its socket and the receiver turned on. The "output meter" or other output indicating device to be used should be properly connected to the receiver as outlined in the section headed "Possible ways of connecting the output meter," in Art. 638.

(b) Now adjust the test oscillator so it is operating at the intermediate frequency specified by the receiver manufacturer (let us assume this is 175 kc). Connect the "Ant" terminal of the oscillator to the "control-grid" terminal (cap) of the *last* i-f tube. Connect the "Gnd" terminal of the test oscillator (usually the "shield" on the previous wire), to the "cathode" terminal of this tube. All the late superheterodyne receivers use screen grid tubes in the intermediate stages. Where 227 type tubes are employed in the i-f stages, as in some of the earlier models, instead of coupling the oscillator to the control-grid cap of the screen grid tube as mentioned, it should be connected to the "grid" terminal of the 227 type tube. This may be done conveniently by removing the tube from its socket, wrapping the "bared" end of the wire

tightly around its "grid" prong, and then placing the tube back in its socket (with the wire still making contact with the "grid" prong).

Usually there are two i-f stages, though in many sets only one stage is used. The primary and secondary coil of each stage is tuned by means of a small semi-variable 2-plate condenser of the "postage stamp" type. The interior of a typical intermediate-frequency tuning unit with its shield removed, is shown in Fig. 285. The primary and secondary coils are of the duolateral type mounted on a wooden spacing-bar. The adjustable tuning condensers in the base of the unit, are those which must be adjusted. They are usually constructed so that a screwdriver is all that is required in order to turn the adjusting screw on each one. Therefore, in a two-stage i-f superheterodyne receiver there will be 6 adjustments, and where only one stage is employed, 4 adjustments will be found. The secondary tuning condenser and then the primary condenser of the *last* i-f transformer should be adjusted for maximum output. Next, the test-oscillator coupling lead should be connected to the control-grid cap of the 1st i-f tube, where the receiver has two i-f stages, and adjustment of the condensers in that stage made for maximum output. To tune the 1st i-f transformer, the test-oscillator "Ant" lead is coupled to the control-grid of the 1st detector tube, and the test-oscillator "Gnd" lead is connected to the "cathode" of this tube. The secondary and primary tuning condensers are now adjusted until maximum output is indicated on the output meter.

Adjusting band-pass i-f tuners of the superhet: Some manufacturers have designed the intermediate-frequency stages of their superheterodyne receivers with a band-pass effect so their tuning curve is flat-topped in order to minimize the suppression of sideband frequencies with the resultant poor high-frequency note reproduction. With these i-f amplifiers, no appreciable change in output meter reading should be obtained when the test oscillator frequency is shifted from 171 kc to 179 kc (for a 175 kc amplifier). In other words, any drop which may occur in the output should be the same when the test-oscillator frequency is shifted from 175 kc to 171 kc as it is when it is shifted from 175 kc to 179 kc. This will indicate that the flat-topped portion of the tuning curve of the i-f amplifier is properly centered at 175 kc. The reader should study (C), (D), (E), (F) and (G) of Fig. 257 at this point to properly understand this.

Aligning the oscillator of the superhet: After aligning the i-f stages, the adjustment provided on the receiver oscillator stage tuning condenser section should be adjusted next. This is one of the most important operations in the entire proceedure, and it determines the dial settings at which broadcasting stations are received.

The test oscillator should be connected to the "Ant" and "Gnd" terminals of the receiver exactly as specified for aligning t-r-f receivers, (see Art. 638). The oscillator tube should be in its proper socket in the receiver. Adjust the test oscillator to a frequency near the high-frequency end of the broadcast band. Now vary whatever capacity adjustment is provided on the set oscillator stage tuning condenser section, until maximum output is obtained, as indicated by the output meter. Repeat this at several other frequencies in the broadcast range. This insures that the frequency of the receiver oscillator will always differ from that to which the r-f and first detector tuning circuits are tuned, by a fixed frequency equal to that for which the i-f amplifier is designed,—for any setting of the receiver tuning dial.

In some cases, the receiver pointer dial may have shifted in relation to the condenser shaft. This can be checked and adjusted by noting whether the kilocycle marking on the set dial corresponds with the frequency of the oscillator when the adjustments on the set oscillator condenser are being made.

Aligning the r-f stages of the superhet: The tuned circuits of the radio frequency stages, (if any are employed), and the first detector stage, are aligned next. With the oscillator still connected as before, those sections of the gang condenser which tune these stages, are aligned in exactly the same way as explained for t-r-f receivers in Art. 638. The test oscillator is operated at several broadcast frequencies,—preferably starting at the high-frequency end of the dial. Proper adjustment is made until maximum output is obtained in each case. This completes the proceedure for aligning all of the tuned circuits of superheterodyne receivers.

REVIEW QUESTIONS

1. What is meant by "continuity" of a circuit?
2. Describe the process of testing a circuit for continuity.
3. Draw a diagram of the plate circuit of a vacuum tube in which the primary of an r-f transformer, and a voltage-dropping resistance are connected in series. A grid-bias resistor is connected between cathode and ground (B minus). Explain how to locate the trouble and determine its nature.
4. A short-circuited primary winding in an audio transformer is suspected as the cause of trouble in the receiver. The resistance of the primary is normally 2,000 ohms. Draw a circuit diagram, and explain how you would test the transformer.
5. How would you check the value of a grid-bias resistor supposed to be of 3,000 ohms resistance?
6. Suppose the by-pass condenser across this grid-bias resistor is of 1 mf. capacity. If this condenser were short-circuited, what effect would it have on the operation of the receiver? How would you test the condenser?
7. What is the first step in servicing an inoperative receiver?
8. Explain how the circuits terminating at a tube socket may be tested by means of separate instruments.
9. What is the advantage of the use of a set analyzer or tester instead of separate meters, for testing receivers?
10. Explain briefly the circuit arrangement and operation of a set analyzer.
11. Draw the circuit diagram of a battery-operated modulated oscillator which may be used for test for testing and lining up the radio-frequency and intermediate-frequency tuned stages of a superheterodyne receiver.
12. Explain how the tuned circuits of a superheterodyne receiver are lined up with a device of this kind. What is the purpose of the output meter used in this work?
13. What does failure to obtain voltage readings at the following points indicate in a receiver; (a) across the filament; (b) from plate to cathode; (c) from cathode to control-grid?
14. Explain in detail how you would proceed to diagnose the trouble and locate it definitely in a 5-tube t-r-f a-c tube electric receiver.
15. Explain the effect of a shorted filter condenser in a power supply unit. If the condenser is one of those in a condenser block, how could it be tested and replaced?
16. Obtain a picture wiring diagram of a simple battery-operated radio receiver, or better still, obtain a complete receiver chassis. Examine the parts and arrangement used in it and tell what type of circuit is employed. Give reasons for your answer.
17. Carefully trace the filament wiring of the receiver of question 16, and draw a complete schematic circuit diagram of it. Draw the diagram neatly and carefully.
18. Now trace all the plate circuits, and draw them in on the diagram.
19. Trace all the grid circuits, and draw them in.
20. Trace all remaining circuits and draw them to complete the diagram.
21. Repeat questions 16 to 20 for a "B" power supply unit.
22. Repeat question 16 for an a-c tube electric receiver.
23. Repeat questions 17 to 20 for this a-c tube electric receiver.
24. What is a 4-gang tuning condenser? What is the object of using "gang" condensers in modern radio receivers?
25. Four sections of a 5-gang tuning condenser in a t-r-f receiver are set at such capacity that they each tune their respective tuning coils to 1000 kc. The fifth section has been jarred out of alignment so that it is tuning its tuning coil to 990 kc at this setting. Explain in detail just what effect this will have on the operation of the receiver. How may it be corrected?

CHAPTER 36

SOUND MOTION PICTURES

GENERAL CONSIDERATIONS — GENERAL METHODS USED — SOUND-ON-DISC RECORDING SYSTEM — SOUND-ON-DISC REPRODUCTION — THE FADER — LOUD SPEAKERS — SPEECH AMPLIFIER — NON-SYNCHRONIZED MUSIC — SOUND-ON-FILM SYSTEM — THE LIGHT VALVE — REPRODUCING — SOUND-ON-FILM MOTION PICTURES — R. C. A. PHOTOPHONE SYSTEM — SPLICING FILM — COMPARISON OF SOUND-ON-FILM AND SOUND-ON-DISC SYSTEMS — REVIEW QUESTIONS.

640. General considerations: The rapid spread of the exhibition of sound motion pictures (commonly called talkies) in theatres, has aroused widespread interest in the methods employed in recording and reproducing the sounds accompanying the picture. The fact that radio equipment in the form of electrical phonograph pickups, photoelectric cells, powerful audio amplifiers and loud speakers are used in this work, makes a discussion of the prinicples involved, and the methods used, very appropriate here.

641. General methods used: There are two fundamental methods which are used in practice to synchronize sound with motion pictures. In the first, a disc record somewhat similar to the home phonograph disc is employed (Vitaphone System). This is commonly known as the *sound-on-disc* system. In the second system, an optical recording on a sound track is imprinted either along the edge of the motion picture film, or in some cases, on a separate film run in synchronism with the picture. The latter method is employed in the Fox Movietone, Phonofilm, and Photophone systems. This is commonly known as the *sound-on-film* system. The Vitaphone and Movietone methods were developed in the Bell Telephone Laboratories, and the Photophone by the Radio Corporation of America. All of these systems are being employed at the present time. They have revolutionized the motion picture industry.

642. Sound-on-disc recording system: The principle of the Vitaphone system, is to make a phonograph record of the sound simultaneously with the taking of the picture, and then play this record with a phonograph pick-up unit fed to amplifiers and loud speakers, while the picture is being projected on the screen. The sound is projected in absolute synchronism with the picture.

When the picture is being filmed, the sound is picked up by several microphones located at advantageous positions in the studio. These feed into the "mixing panel" which is operated by a man located in a special glassed-in "monitor" or "mixing room," overlooking the scene of action (see

Fig. 483). The operator views the stage upon which the action takes place, through several thicknesses of glass to make the "mixer room" absolutely quiet. This is one of the most important parts of the sound apparatus in the entire circuit. The inputs of all the microphones are blended here and the operator can increase or decrease the input of any one microphone at will. Thus he is able to "pull up" or "tone down" the voice of a star, the music from the orchestra, etc.

The director on the floor, controls the recording, etc., by means of a signal box which contains signal lights and push buttons for signalling the

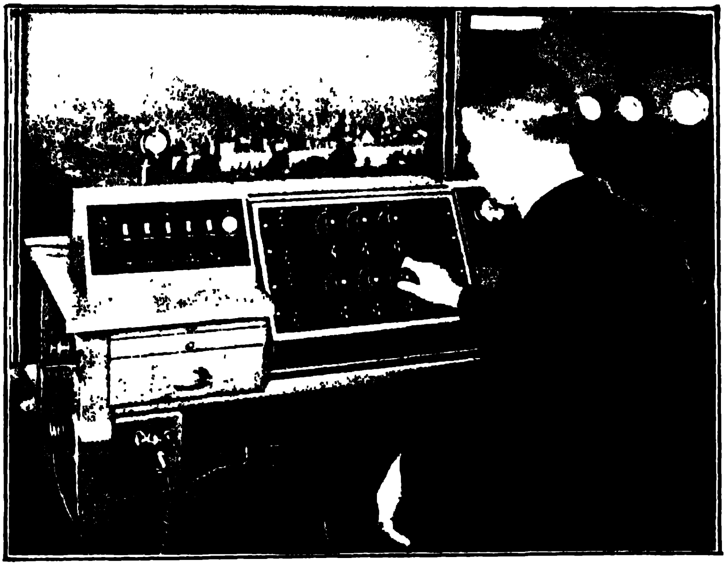


Fig. 483—The "mixer room" of a United Artists sound motion picture studio. Here the output of the various microphones used during the filming of a picture are blended together in the proper proportion by the operator.

various stations concerned in the filming and recording. A scene on a "set" in a sound stage studio just before the scene is "shot", is shown on the left of Fig. 484. All direction is done by motion of the hands or arms. In this picture, all parts of the set are plainly seen. The microphone M is suspended from a boom at the left, almost directly over the star who is seated, and out of visual range of the cameras taking the scene.

Every possible effort is made to prevent the pickup and recording of undesirable noises during the filming of the scene. Arc lights in motion picture filming have given way to huge noiseless incandescent lamps L, as the objectionable sputtering and hissing noises of arc lamps would be recorded along with the rest of the sounds.

The cameras are enclosed in sound-proof housings which may be easily opened to permit access to the mechanism. Two types of these sound deadeners are employed. The type shown at B at the left of Fig. 484 consists of a sound-proof box B

as shown. The type shown at the left of Fig. 485 consists of a soft-padding blanket enclosure placed over the entire camera. This is commonly called a "blimp". A box-like housing which encloses cameras for outdoor work is also shown at the right of Fig. 485. This machine contains the camera with its sound proof enclosure at the top. This can be swung in any direction and raised up or down vertically. This machine can move about the stage under its own power, carrying the cameraman and his assistant, when taking scenes of moving objects. In the past, a crew of 3 or 4 "grips" was necessary to keep the camera in motion for such a "shot". The camera mechanism is coupled to an electric driving motor by a noiseless flexible shaft.

The studio in which sound pictures are recorded, must be either sound-proof or acoustically treated, so that sounds from outside cannot penetrate and be picked up

Courtesy Universal Pictures Corp.

Fig. 484—Left: A scene on a sound picture "set." Note the condenser-type microphone M over the seated star. The sound-proof compartment B over the camera is visible. Right: Taking outdoor scenes with the cameras placed in sound-proof enclosures

by the microphones within the studio, and thus interfere with the sound record being made. The acoustic treatment also prevents reverberations, echos and other objectionable sounds. If the studio were not treated in this way, the rate of sound absorption within the studio would be so low that words spoken in an ordinary tone of voice would be heard for several seconds afterwards, which would mean that the dozen or so syllables following the word in question would blend into the decaying sound of the word, and render understanding extremely difficult.

On the other hand, a sound-recording studio must not be too "dead." It should have some "life" to it. The "life" of a studio is a function of the walls surrounding the studio, the ceiling, the floor, and the number of persons and articles within it. When a sound shot is being made, it is obviously desirable to pick up only the sound pertaining to the action being filmed. All extraneous noises only aid in bringing up the "ground noise", and are therefore a detriment to high-grade recording.

From the monitor room, the signal currents are fed to powerful 4 or 5-stage audio amplifiers which greatly increase their strength. Then the currents are fed to the mechanical recorder which cuts the record. The records used in the Vitaphone system are "laterally" cut, i.e., the groove is of a constant depth and oscillates or undulates laterally about a smooth spiral. The cut is about 0.0025 inches deep and 0.005 inches wide. The space between grooves is about four mils (0.004 inches). The number of grooves per inch varies between 80 and 100 in usual practice. The

linear speed of the record past the cutter (or reproducing needle) varies between 70 and 140 feet per minute. Recording is accomplished by a cutting stylus which is made to vibrate in strict accordance with the energizing current. Fig. 486 shows a recording room, in which two "disc recording machines" developed by the Bell Telephone Laboratories are installed. They are constructed to be mechanically rigid, and are arranged to be driven synchronously with the motion picture. The turn-

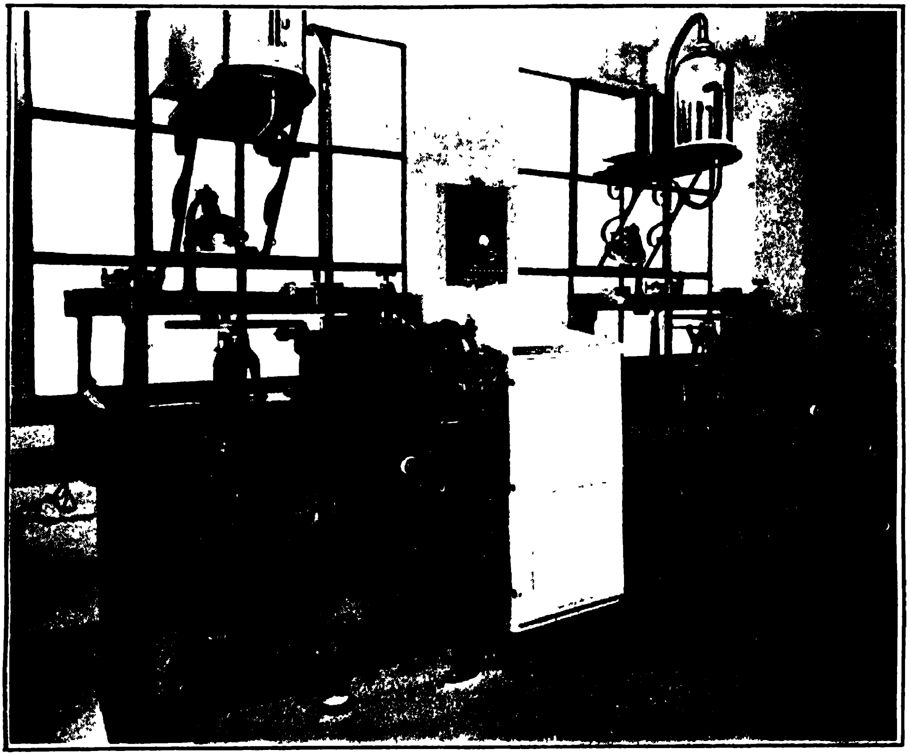
Fig. 485—Left: Cameras mounted on the end of a long crane during the filming of a war scene by Universal Pictures Corp. The cameras are covered with sound-absorbing blankets or "blimps"
Right. A special sound proofed camera used by Paramount Pictures Corp. It is mounted on wheels, and motor driven so it can move about under its own power.

tables upon which the "wax" record is placed, may be seen at the left of each machine.

The original disc or "wax" as it is called, is of a special metallic soap from 13 to 17 inches in diameter and about one inch thick. This is given an initial high polish, and is then mounted horizontally on the turntable driven at a uniform rate of speed and synchronized with the film passing through the cameras which are taking the scenes. This synchronization is accomplished by electrical means of a highly technical nature. (For further detailed information on this subject, the reader is referred to the Vol. 7, No. 3 issue of the Bell Laboratories record). The cutting stylus cuts from the center toward the outer edge of the disc. The turntable rotates at about 33 1/3 revolutions per minute, this is nearly ½ the speed

at which a home phonograph disc rotates. The sound picture disc is designed to rotate slower so that a longer sound program may be recorded on a single record.

After the wax has been cut, it is of course desirable to be able to "play" it at once in order to detect any flaws. For this purpose, a special reproducer known as the "play-back" is used. This is made extremely



Courtesy Bell Telephone Laboratories

Fig. 486—Disc or "wax" recording machines in the recording room of the United Artists Studio in Hollywood.

light so as to produce no appreciable wear on the relatively soft wax record.

Ordinarily, one machine contains a "play-back" disc which is used by the director to ascertain if his record is as perfect as he wishes it to be, as regards voice and sound. The other disc is the "master disc" from which the reproductions for the final picture are made. This arrangement is very similar to the process of making phonograph records. In some cases, phonograph artists make from six to twenty wax discs before the perfect one is decided upon.

The glass jars above the machines in Fig. 486 form a depository for the wax shavings from the disc being recorded. A suction process is

utilized to suck the small wax shavings into the jar. These are emptied when the jar is near the filling point. A microscope is provided with each machine to enable the operator to carefully examine the recordings made.

If the wax is satisfactory it is then dusted with a fine conducting powder, and electroplated to produce a negative copy of the recordings. This is called the "master". By successive electroplating steps, duplicates of the "master" known as "stampers" are obtained, from which large quantities of "positive" playing records can be made. A thousand or more pressings can be made from a single "stamper".

Great success is being attained in the perfection of methods for re-

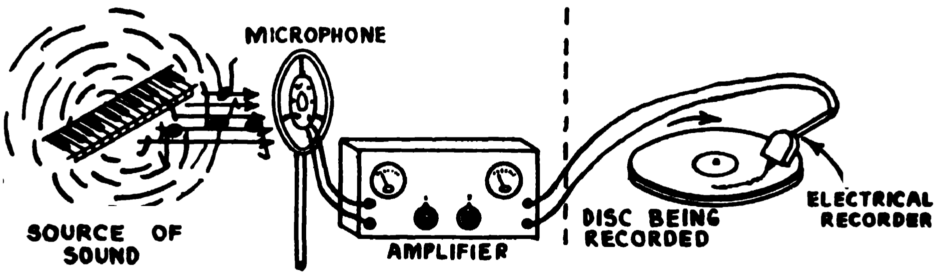


Fig. 487—Sound-on-disc recording system. The sound waves act on the microphone, causing motion of its diaphragm and variations in the current through it. These are amplified by the audio amplifier and actuate the electrical recorder which cuts a spiral groove into the "wax." Tiny wiggles are cut into the groove in accordance with the sound waves. (See left of Fig. 404.)

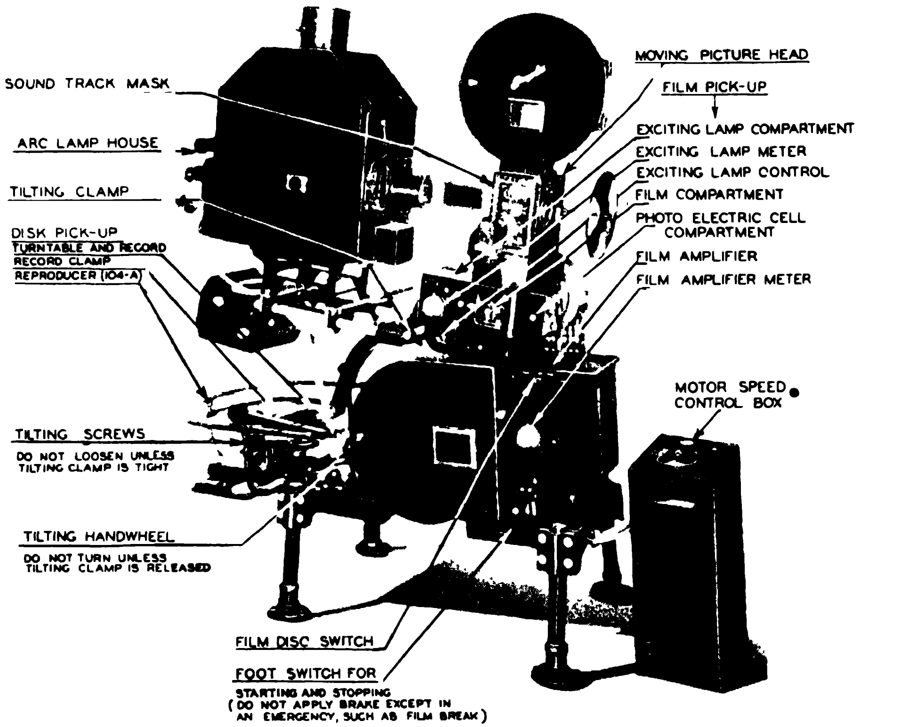
cording parts of disc records so that the material may be entirely rearranged, portions being deleted or added. This is called "dubbing" the record. This of course is a great advantage for removing objectionable sounds for censorship purposes, etc.

An outline picture of the recording process used in the sound-on-disc system is shown in Fig. 487. The sound waves are impressed on the microphone at the left, which converts them into varying electrical currents. These variations are amplified greatly by the audio amplifier and are then fed to the electrical cutter or recorder which cuts corresponding "wiggles" into the spiral groove on the "wax" disc.

643. Sound-on-disc reproduction: In the sound-on-disc system, the sound records are supplied to the motion picture houses along with the respective motion picture films. One disc is made for each reel of film but a spare disc is supplied with each reel in case of damage, breakage, and so forth. In the projection booth of the theatre, the horizontal turntable is mounted beside each projection machine as shown in Fig. 488. One "frame" at the beginning of the film is marked to go at the starting point. When the film is threaded into the machine the starting point is located at the picture aperture, and the needle of the phonograph pickup (this is called a *reproducer* in sound picture work), is placed in the inside

groove of the disc record, at the point marked "start". The disc turntable is rotated by the same electric motor which drives the film through the projector, so that synchronism is maintained between scene and sound throughout the entire showing of the reel of film.

While the film is running at 90 feet per minute, the disc turntable is revolving at 33⅓ r.p.m. The equipment includes a special vacuum tube speed-control system, for keeping the speed of the film and disc constant, so that the film running at the speed of 90 feet per minute keeps



Courtesy Electrical Research Products Corp.

Fig. 488—A motion picture projector equipped for both sound-on-disc and sound-on-film reproduction. For the former the turntable and pick-up (reproducer) shown at the left are employed.

constant within ½ of 1%. The electric motor rotates at exactly 1,200 r.p.m. even though the line voltage may change. This equipment is contained inside of the motor speed-control box shown at the right of Fig. 488. The phonograph pickup unit or "reproducer" is usually of the electromagnetic, oil-damped type, of refined design so as to produce good fidelity over a wide frequency band. This type of pickup was described in Article 543. The sound frequencies reproduced by commercial sound picture systems range from about 30 to 6000 cycles per second.

644. The fader: As in the case with the exhibition of ordinary silent motion pictures, two or more projectors must be used alternately

rtesy Electrical Research Products Corp.

Fig. 489—The method of setting the record at the "starting point" in the sound-on-disc system The needle of the phonograph pickup unit is placed in the starting mark on the disc

to present a continuous program. At the end of a record and reel of film, the music and speech coming from one machine must be blended perfectly into that starting from the new one, just as the picture from the

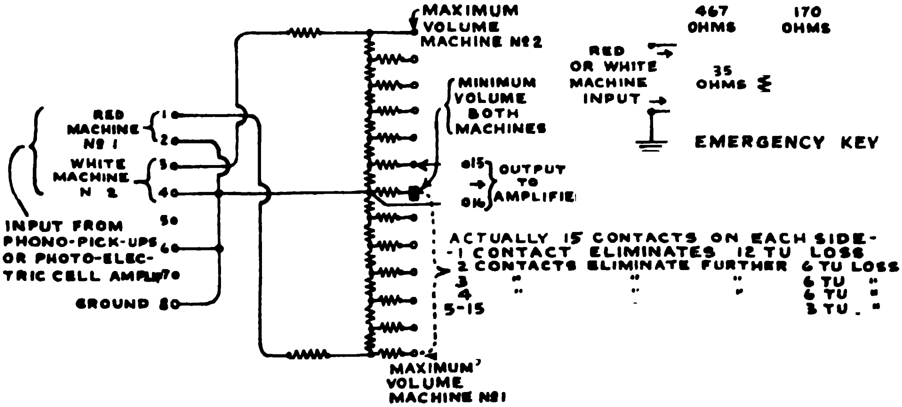
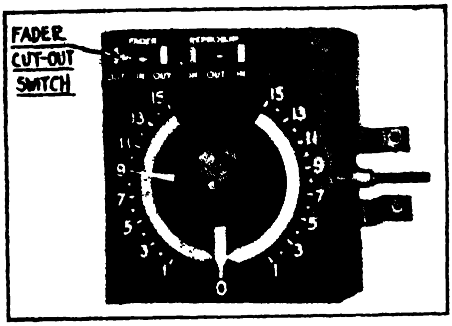


Fig. 490—A typical "fader" resistor arrangement employed in sound picture work—see Fig. 491

finished reel is faded into that from the next. When a cue spot in the picture flashes on the screen, the operator sets the second machine in mo-

tion. Immediately thereafter, the "change-over" is made. This is done on the screen by closing the iris shutter of the expiring projector and instantly opening the shutter of the new machine. The change-over between the two sound records is accomplished by a device known as a "fader".



Courtesy Electrical Research Prod. Corp.

Fig. 491—A typical Fader control cabinet. The Fader control knob may be turned to either side to play from either reproducer. The graduations indicate the volume level position—see Fig. 490.

At the end of each sound disc (or sound film) the sound recordings overlap. Then at the beginning of the next one as the starting projector goes into operation, the fader control knob is turned, reducing the output of

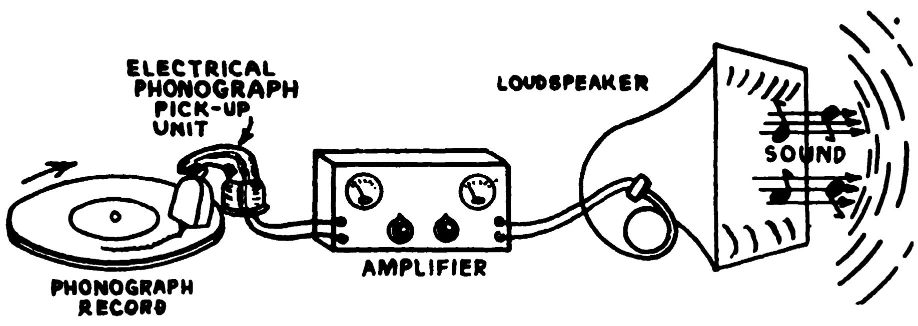


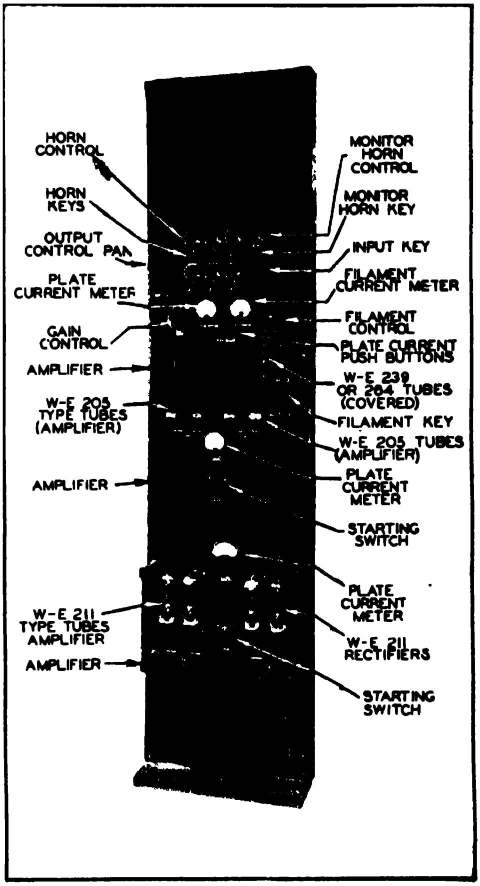
Fig. 493—A simplified diagram of the reproducing arrangement employed in the sound-on-disc system. The wiggles in the spiral groove of the phonograph record cause the needle in the pick-up unit to vibrate. This causes a corresponding varying e.m.f. to be generated in the coil of the pick-up. The variations in the e.m.f are greatly amplified by the powerful amplifier, and are fed to the loud speakers which convert them to corresponding sound waves.

the expiring record gradually to zero and simultaneously increasing the loudness of the sound from the new record to any desired volume.

The fader system commonly used in sound picture work is shown in Fig. 490. Input terminals 1-2 and 3-4 from the machines, are shown at the left. The fader resistor really consists of a potentiometer system.

Terminal 16 is fixed and connects to the center of the resistor. Terminal 15 connects to the moving contact arm which may be moved either up or down from the "minimum volume point" contact. The positions for minimum and maximum volume are shown on the diagram. The front view of the fader control with the knob and indicating dial, is shown in Fig. 491. The changeover from one reel and record to another, is barely perceptible to the audience when done by a skillful operator.

The fader resistor taps are so arranged, that in the lower range used in changing between projectors, the steps are rather large; whereas in the upper range, the volume changes in scarcely perceptible steps. The fader can therefore be used as a volume control, and also for equalizing the volume of sound obtained from different records. As the acoustic characteristics of a theatre, due to its dimensions, architectural features, and especially the size of the audience, varies considerably from time to time, the fader serves also as a convenient means of controlling the volume of the reproduced sound in order to obtain the most natural and pleasing reproduction.

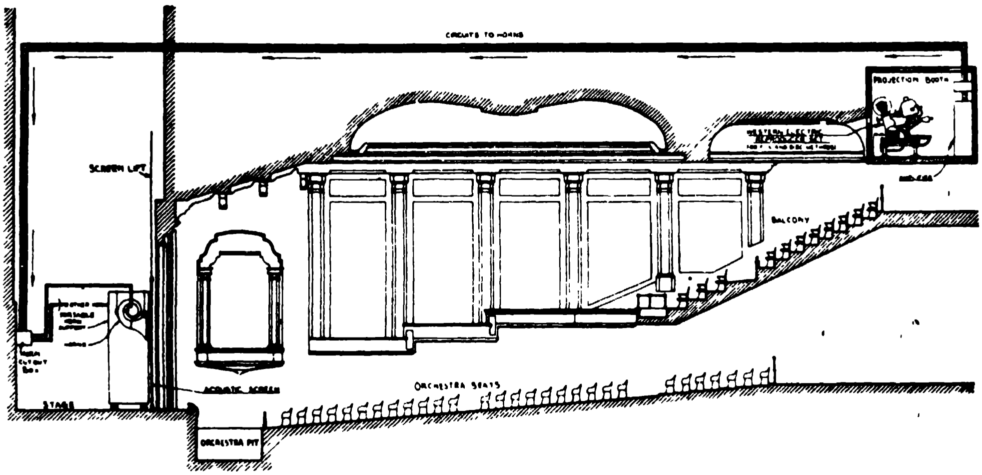


Courtesy Electrical Research Prod. Corp.

Fig. 492—A typical rack-and-panel audio amplifier and output control panel employed in sound picture work.

644A. The audio amplifiers: After having been adjusted by the fader, the varying audio voltages go to a series of special amplifiers, where they are enormously amplified. These amplifiers are designed so that all frequencies from about 40 to 10,000 cycles are amplified about equally. The amplifier is usually built in three units. The first consists of a three-stage resistance coupled amplifier using low-power tubes. The second unit consists of a push-pull stage of medium-power tubes heated by alternating current, while the third unit consists of a push-pull stage using high power tubes with filaments energized by alternating current. Plate potentials for all tubes are obtained from rectified alternating current supplied by rectifier tubes, and smoothed out by a suitable filter unit.

For small theatres, only the first two units are used, while for large theatres one or possibly two of the third type are also used, to obtain sufficient volume of sound for the auditorium without overloading. The three units are capable of multiplying the *energy* of the reproducer nearly one-hundred-million-fold. An amplifier of this type is shown in Fig. 492. The various parts are labeled directly on the illustration. Notice that it is built in standard rack-and-panel form so as to take up a very limited amount of floor space. The output from the last amplifier stage is brought to an output-control panel mounted at the top of the amplifier rack. This consists of an autotransformer having a large number of taps, which are connected to a number of dial switches. The loud speakers are connected



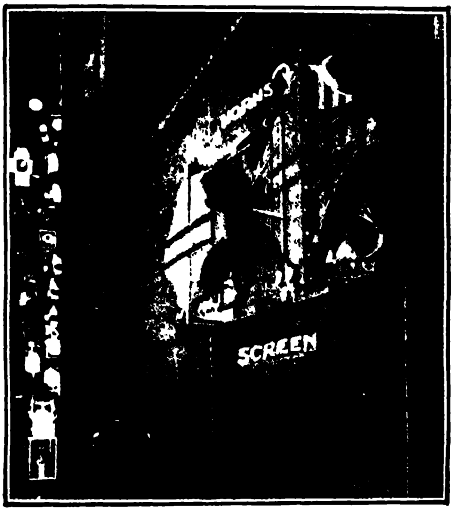
Courtesy Electrical Research Products Corp.

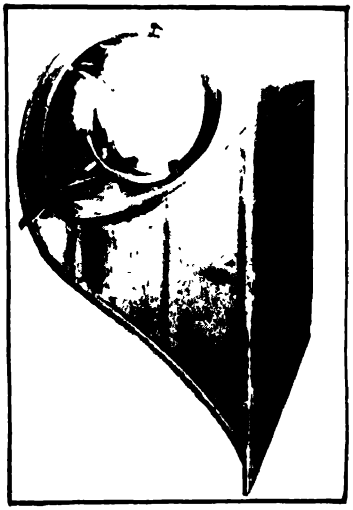
Fig. 494—A longitudinal cross-section view of a typical theatre showing the installation arrangement of the sound equipment. The exponential horns are mounted about 2/3 the way up from the bottom of the screen. The circuits run to the amplifier panel in the projection booth at the upper right

to these switches, so that the impedance of the amplifier output can be matched to the number of loud speakers it is desired to use at any time. This makes the individual adjustment of volume of any loud speaker possible when necessary. An outline diagram showing the main parts in a sound-on-disc reproducing system is shown in Fig. 493. An electrical phonograph pickup reproducer unit playing from the record at the left, produces varying electric voltages which are amplified by the high-gain audio amplifier system, and then fed to the loud speakers where the sound is reproduced for the audience.

645. The loud speakers: Large exponential horn-type loud speakers with electro-dynamic driving units of the type shown at the left of Fig. 358 and in Fig. 359 have been used almost exclusively in sound motion picture installations on account of their very high efficiency. The loud

speakers have been greatly improved and are being designed to take up as little space as possible behind the motion picture screen. In some installations four loud speaker horns are placed at the front of the theatre —two being placed in the orchestra pit and directed more or less toward the balconies, the other two being located behind the upper edge of the screen and directed downward toward the rear floor seats. In recent installations only two speakers are used. These are mounted about 2/3 of the way up from the bottom of the screen as shown in Fig. 494. The actual installation of two of the newer flat-type speakers which are mounted in such a way that they are raised or lowered as a unit with the motion picture screen, are shown at the left of Fig. 495. Notice the bracing to





Courtesy Electrical Research Prod. Corp.

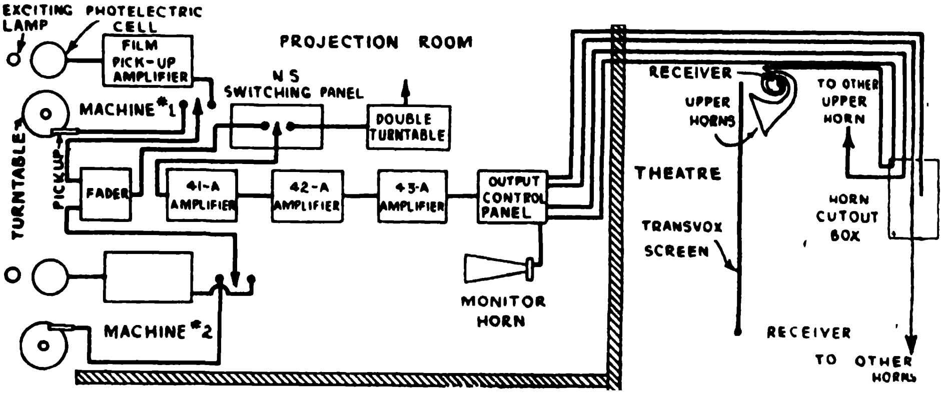
Fig. 495—Left: Two flat-type exponential horn speakers mounted directly on the back of the motion picture screen of the Roxy Theatre in New York City. The speakers are lowered and raised with the screen. Each speaker has 4-driving units on it. Right: A typical coiled-type exponential horn speaker 30" deep, employed in sound picture work.

strengthen the speakers at the back, and the use of 4 driving units on each speaker. This type of speaker is also very advantageous in theatres where the screen is located very near the rear wall of the theatre. At the right of Fig. 495 is shown one of the coil-type exponential horns which have been used extensively. Notice that this provides for the use of two driving units (see Art. 471).

There are several reasons for placing all of the horns at the front of the theatre rather than distributing them throughout the theatre.

One of these is what may appear to be a lack of synchronism between the moving picture and the sound; that is to say, the ear may subconsciously detect a fraction of a second difference between the movement of the actor's lips and the reception of his voice. This is not a technical defect but a perfectly natural law that governs the difference between the speed of light and the speed of sound. Now the movement of

light is practically instantaneous (186,000 miles per second), so that the man sitting in the farthermost row of a large theatre actually sees the image on the screen at the exact instant that it appears on the screen, while the sound, coming the entire length of the theatre, strikes his ear a fraction of a second later, since it moves at the rate of only 1130 feet per second. The natural reaction to this, is to wonder why loud speakers could not be placed in all the different parts of the theatre. However, a careful analysis of this suggestion will make the drawbacks self-evident. A cure of this kind would be worse than the original ill, due just to this very time-lag. It is true that the spectator in the far row would hear the sound from the speakers in the rear of the theatre at exactly the same time that he would see the image, but a fraction of a second later he would hear this same sound coming up from one of the speakers located in the front of the house. The result would be a fuzzy or blurred sound to every one in the house, as the spectator down front would also hear the response from the speaker located at the back of the house later than from the speaker nearby. For this reason, it has become standard practice to place all loud speakers at the front of the theatre, and facing out toward the audience. Fig. 496 shows a typical installation



Courtesy Bell Telephone Laboratories

Fig. 496—Block diagram showing the typical sound picture equipment employed in a theatre. The various amplifier and control units are shown. The signal impulses originate in the photoelectric cell at the upper left, are greatly amplified, and then progress through the equipment to the loud speaker horns behind the screen.

of equipment for sound pictures. The directive sound characteristic of the particular horns used is important, since it is responsible for the illusion that the sound comes directly from the lips of the persons appearing on the screen.

If speakers which radiate their sound over a wide angle are used, the sound appears to be coming from a point some distance behind the screen. A special type of screen, reflecting light well, but transparent to sound, is used for the picture, so that the sound from the speakers located behind the screen is not seriously interfered with.

A small monitoring horn is placed in the projection booth for the convenience of the operators to enable them to follow the program continuously, and to instantly detect any trouble which may occur in the reproducing system.

646. Speech amplifier: In addition to their convenience as a part of the sound motion picture equipment, the audio amplifier and loud speakers may also be used as a public address system for speech amplification. Microphones can be concealed in the floor lights and placed in

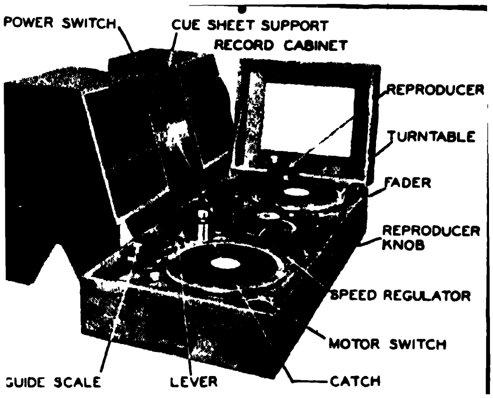


Fig. 497—Equipment for producing non-synchronized music accompaniment for silent pictures. Two turntables and reproducers are provided, together with record cabinets. The usual Fader, amplifier and loud speaker equipment must also be employed.

Courtesy Bell Telephone Laboratories

such positions that they will not be affected by the sound waves issuing from the horns. A microphone is also installed in the manager's office for announcements to the audience in the theatre.

647. Non-synchronized music: By means of the auxiliary equipment shown in Fig. 497, the sound picture system can also be used to pro-

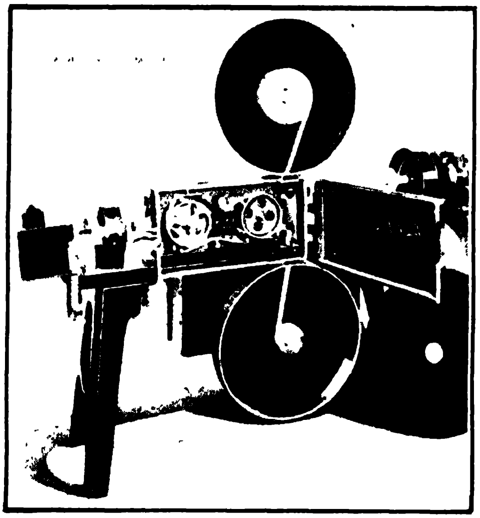
Courtesy E. R. P. Corp. *Courtesy R. C. A. Corp.*

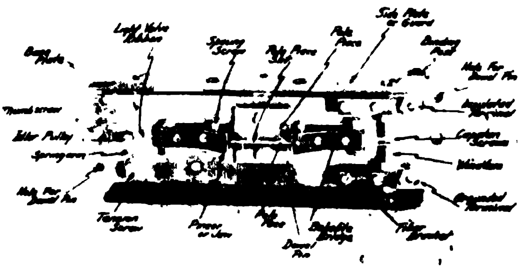
Fig. 498—Left: Enlargement of Movietone sound recordings on a motion picture film. The sound recordings consist of the parallel light and dark lines "T" at the right. Right: Enlargement of sound recordings employed in R. C. A. Photophone system. The recordings at T consist of a uniformly-dark band of varying width and area.

vide non-synchronized music as an accompaniment to silent pictures with which no sound recordings are provided. There is a cabinet containing

two motor-driven turntables, each having a pick-up unit and means for locating it accurately on a record. A fader is provided to make continuous playing possible from one record to the next. Two record cabinets are also supplied, as shown. This is sometimes called an "electrical transcription" program, and may also be employed for supplying music during the intermission period on the program. The same amplifiers and loud speakers are used, as are employed for the synchronized speech and music.

648. Sound-on-film system: There are two methods of sound film recording in general use. In the Movietone method, the variations in sound are produced by variations in light through the sound track "T" of variable density and constant width along one edge of the film. The





Courtesy Elect. Research Prod. Corp.

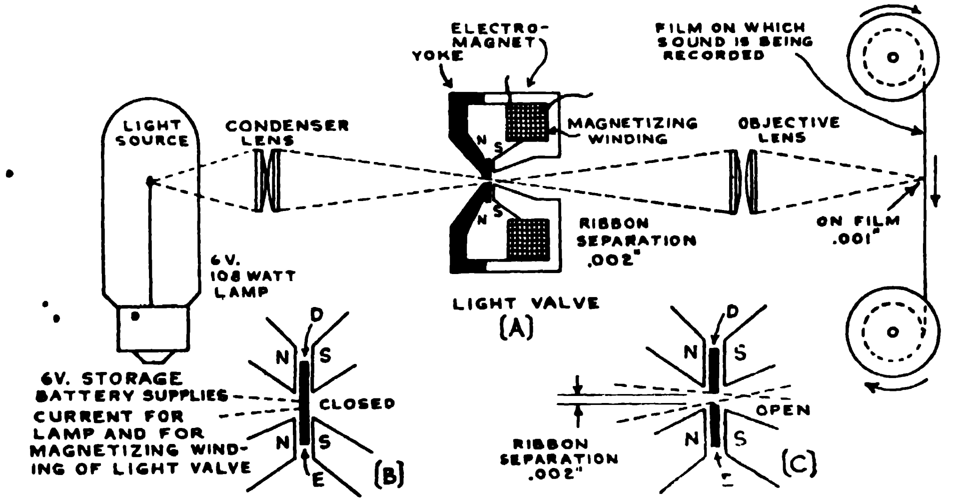
Fig. 499—Left: A sound-on-film recording machine employed in the motion picture studio.
Right: The light-valve employed for recording the sound track on the film. This is the heart of the entire recording system

film also contains the visual pictures "P", as shown at left of Fig. 498. In the R.C.A. Photophone system, the variations in sound are produced by variations in the area of the uniformly dark sound track "T" along one edge of the film, as shown at the right of Fig. 498. The taking of the picture and method of projecting it are quite similar in both systems as we shall see later.

In the Movietone system the sound track on the film is recorded in the machine shown at the left of Fig. 499. This is mounted in a separate room off the "set". The recording machine is driven by a three-phase synchronous electric motor which is supplied with current from the same source as is the camera motor. Both motors are electrically interlocked so they both run at exactly the same speed.

649. The light valve: The heart of the recording machine is the *light valve.* This is shown at the right of Fig. 499. It consists of a loop of duraluminum ribbon, suspended in the narrow slit between two pole-

pieces of an electromagnet as shown in the illustration. The duraluminum ribbon is .006 inch wide and .003 inch thick. Its ends are secured to separate insulated windlasses stretched tight by a spring-held pulley. The ribbon is looped around the idler pulley shown at the left. In this way, the two parts of the ribbon form a very narrow slit approximately .0003 inch wide, between them, at the part where they pass between the pole-pieces of the electromagnet. The output terminals of the audio amplifier, which follows the microphones, are connected to both ends of this light-valve ribbon. The audio currents flowing through the continuous loop-circuit formed by the two sides of the ribbon, produce varying magnetic fields. These cause the two sides to repel each other and thereby widen



Courtesy Electrical Research Prod Corp.

Fig. 500—Light and optical system for sound-film recording At (A) the beam of light from the light-source is condensed into a narrow beam by the condenser lens. This shines through the slit of varying width between the two sides of the duraluminum ribbon in the light valve. The beam of light which gets through is of varying width, depending upon the recording signal fed to the light valve. This acts on the sensitized negative film which is moved past it at the right, resulting in the sound recordings as shown at T on the film at the left of Fig. 498.
(B) Position of the two sides of the duraluminum ribbon when the slit is closed and no light gets through.
(C) Position of the ribbons when the slit is wide open and maximum light gets through.

the slit between by varying amounts, depending upon the amount of current. The tension on the ribbon is adjusted to tune the valve to about 8,500 cycles to give the best frequency-response.

When the slit between the ribbons in the light valve is placed between the light source and the photographic film, a camera shutter of unconventional design is formed. A diagram of the simple optical system which results, is shown at (A) of Fig. 500. At the left, is the light source which is focused on the very narrow slit between the two sides of the ribbon, onto the light valve, by means of the condenser lens. A very thin band of light passes through the slit in the valve, and is then focused at a two-to-one reduction on the photographic negative film at the right, which is being moved past this slit of light at proper speed. The undisturbed valve opening causes a very thin band of light to appear on the film as a straight line, with its length at right angles

to the direction of the film travel. The width of this pencil of light varies in accordance with the opening of the slit, which in turn, depends on the audio current sent through the ribbon. Therefore the negative film receives exposure to light of variable density, depending on the amount of the opening of the slit. The recordings appear as a series of parallel lines of varying darkness, as shown at the left of Fig. 498.

649A. Sound-on-film recording: The recording of the sound program in the studio, is carried out on a film separate from that which receives the picture. This practice permits the use of two machines to make duplicate sound records. The practice of employing separate negatives for sound and picture also permits the picture negative to be developed and printed separately according to well-established technique, and allows the necessary latitude required in developing the film containing the sound record, for best results.

The recording machine is designed to draw the film from the upper feed magazine, past the valve slit, to the take-up magazine below. This is accomplished at a uniform speed of 90 ft. per minute, by means of two sprocket wheels which engage the film

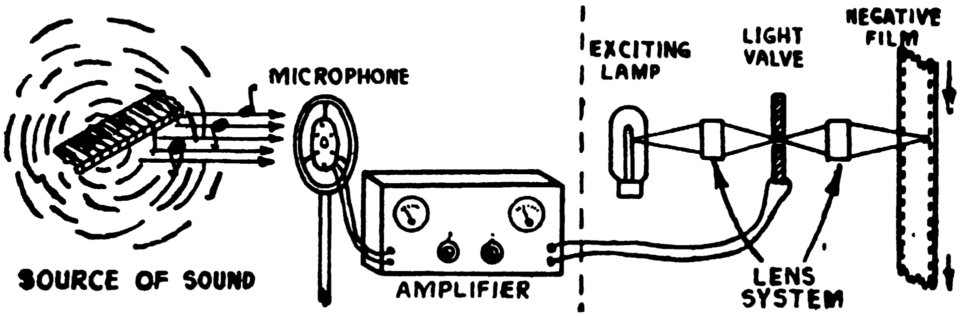


Fig. 501—Simplified diagram of the recording system employed for recording the sound track on the film. (See Figs. 498 and 500.)

perforations. Inside the left hand sprocket, is a photoelectric cell which is affected by the light passing through the "sound track" on the film, so that its amplified curren variations may be heard from a loud speaker used to monitor the recording as it is actually being impressed on the film.

The light source, shown at the left of the machine, is an 18 ampere projection lamp with ribbon filament. Great care is exercised in adjusting, so that the loudest sounds give the maximum allowable exposure. The program is rehearsed until satisfactory arrangements of microphones and amplifier gain is effected, this being judged by the monitoring loud speaker. An outline diagram of the sound-on-film system of sound studio recording is shown in Fig. 501.

Sound picture news reels are usually recorded by a different method in which the heart of the system for changing the electrical currents into light variations, which are in turn applied to the negative film, is a flashing light called the Aeo-Light.

The term "AEO" was derived from the three words, Alkaline Earth Oxide, by taking the first letter in each word. This seemed a fitting term to use, because the coating on the negative electrode of this flashing lamp is an Alkaline Earth Oxide, and it is this coating which gives to the light the inherent properties which make it adaptable to sound pictures.

The Aeo-Light is a tubular-shaped lamp, about six inches long and one inch in diameter, inside of which there is a filament-shaped negative

electrode. Adjacent to this electrode there is a plate, which is the positive electrode. The negative electrode, or filament is covered with barium and strontium. The gaseous content of the Aeo-Light is about as follows: 1½ per cent nitrogen; 3 per cent neon; and 95½ per cent helium.

When about 350 volts, direct current, is applied across the "Aeo-Light" in series with 12,000 ohms, a bluish white glow is established within the tube. The d-c voltage varies with different lights, and is usually made of such a value, that there will be a current of about 10 milliamperes flowing through the Aeo-Light circuit, because with a gaseous tube of this type, after the gap between electrodes has become ionized, the impedance of this path is liable to become lower and lower until it is practically a short circuit. The stabilizing resistor obviates this possibility. When the Aeo-Light is energized with the d-c voltage and normal direct current is flowing through its circuit, it is very sensitive to changes in voltage across its terminals. Therefore, if the alternating current output from the audio amplifier is applied across its terminals, it causes the brilliancy of the glow within the tube to vary in accordance with variations in the applied sound energy.

The Aeo-Light is placed in a tube in the back of the motion picture camera. The inner end of this tube, has a minute slit about 100 millimeters long and 1 millimeter wide, and it is through this little slit that light shines from the Aeo-Light through to the film, which is passing the aperture in the end of the Aeo-Light tube at the rate of 90 feet per minute during the course of operation. In the Fox-Case Movietone system of recording sound pictures used in news-reels, the action being recorded by the camera always bears a constant relation to the sound being recorded, because in this system the sound is recorded on the same negative that the picture exposures are made on and they are, therefore, always in synchronism.

In the studios, the sound track is usually recorded on a separate piece of negative film, and the sound and picture are combined into a single print during the printing process, the picture being printed first, with the sound track masked out, and the sound track is printed last, with the exposed picture masked out so as not to fog it. The Aeo-Light has the disadvantage of giving insufficient light to completely expose the film, and hence limits the amount of power which can be obtained in the reproducing system, without excessive surface noise, but has the advantage of being practically independent of frequency within the audio range.

When scenes are to be recorded "on location", away from the motion picture studio, all of the required electrical recording apparatus must be transported to the place where the picture is being filmed. Special complete groups of recording equipment are employed for this purpose. They are installed permanently in automobiles so as to be readily transported

and available at all times for "location" work. All of the apparatus is arranged on the automobile, in a way which makes it possible to quickly get it into operation. Flexible cables run from the apparatus in the automobile to the recording cameras, etc.

Courtesy United Artists
Fig. 502—A sound truck with all apparatus necessary for recording the sounds with outdoor scenes.

Fig. 502 shows the interior of a sound truck employed by the United Artists studios in making outdoor scenes for talking pictures. Fleets of these units accompany film companies to distant locations to record voices and sounds that synchronize with the photographic action.

650. Reproducing sound-on-film motion pictures: Most moving picture projectors are equipped both with the sound-on disc turntable and reproducer already described, and also with sound-on-film reproducing equipment, so that either type of picture may be exhibited. The sound-on-film reproducing apparatus is located beneath the ordinary projector mechanism as shown in Fig. 488.

As the film leaves the projector mechanism and enters the sound unit, it passes down from the sound gate, where a beam of light from the exciting lamp is concentrated by an optical lens system and aperture containing a slit which brings the light to focus as a fine line across the sound track, (see Fig. 503). The film moves at the uniform speed of 90 feet per minute through the sound gate, and to the take-up magazine below. The film speed is the same as that used during the recording.

The density of each particular line of the sound track, as it passes the pencil of light at the sound gate, determines the amount of light permitted to pass through the film on to the photoelectric cell beyond. The current flowing in the photoelectric cell is therefore modulated in accordance with the density of the lines on the sound track. This photoelectric cell is located on the side of the sound gate away from the exciting lamp. As the sound gate is 14½ inches below the picture gate, the sound recordings are purposely printed on the film 14½ inches in advance of the corresponding picture, so that the sound track and picture will reach their respective gates at the same time, and the sound will be heard at the same instant that the picture appears.

The photoelectric cells commonly used at the present time are of the gas-filled caesium type. A cell of this kind is shown at the right of Fig. 436. The arrangement of the exciting lamp at the left, the sound gate at the center, and the photo-electric cell at the right are shown in Fig. 504. This is an interior view of the sound-head on the projector. A simplified schematic view is shown at the left of Fig. 505. A form of photo-electric cell which is not supplied with a base but which is simply

mounted between two pieces of sponge rubber held by a spring, is shown at the right. This shock-absorbing mounting may be seen by inspecting the photoelectric cell in the compartment at the right of Fig. 504.

The photoelectric cell output is strengthened by a small "head amplifier", (of type shown at the left of Fig. 438 and in Fig. 503), mounted close to the sound unit. The output of this amplifier goes to the "film-disc" switch. The output from either the sound-on-film pickup or the sound-on-disc pickup, (depending upon which is being employed), is carried to the *fader*, which regulates the volume of the sound during the show. From here the current is carried to the main rack-and-panel amplifiers, the output of which passes to the loud speakers located behind the screen, from which the sound issues in synchronism with the action of the picture. The simple schematic drawing of the system employed in reproducing sound-on-film programs is shown in Fig. 506.

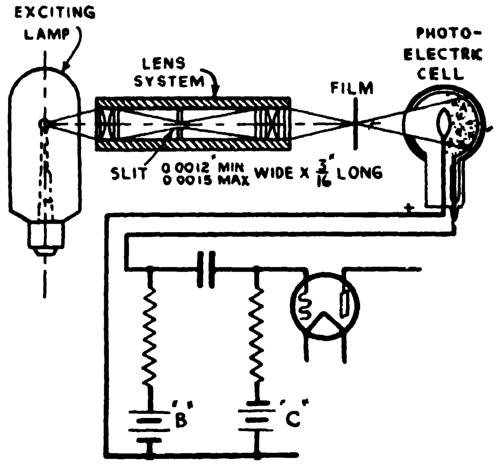


Fig. 503—The exciting lamp, optical system, photoelectric cell, and connection to the first amplifier stage (called the "head amplifier") in the sound-on-film reproducing system.

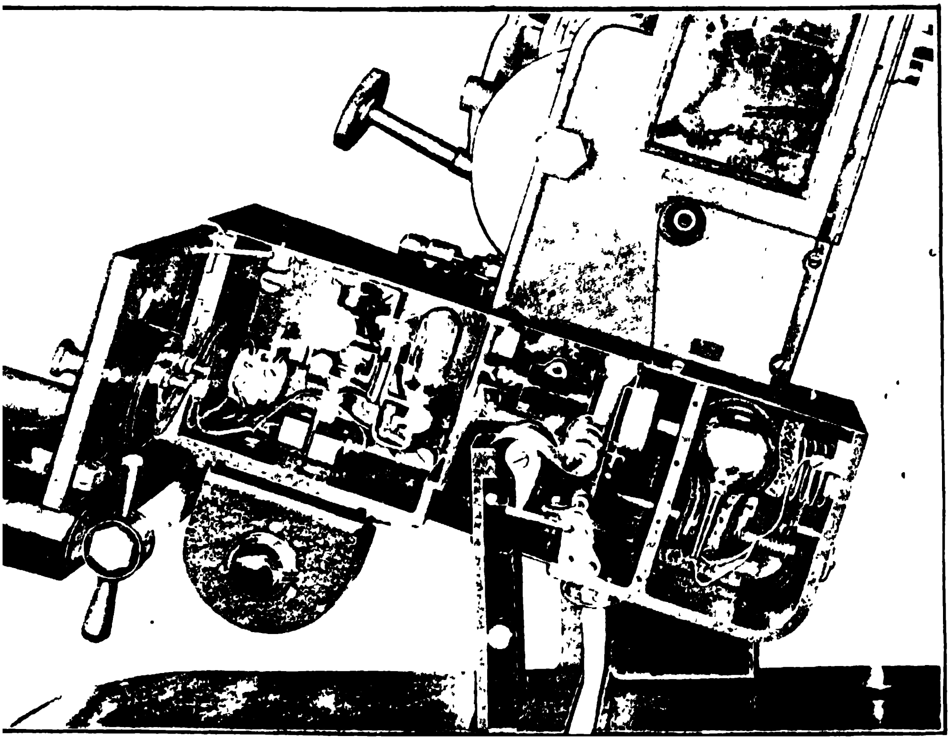
This shows how the narrow slit of light from the exciting lamp shines through the film to the photo-electric cell. The output of the cell is amplified by the audio amplifier, and is finally fed to the loud speaker which produces the sound. The changes in the frequency of the sound, are determined by the number of changes from dark to light and back again per inch length of the sound track. The changes in the intensity of the sound, are determined by the changes in the density or darkness of the lines on the sound track as the film is moved past the narrow film of light, the light and dark lines on the sound track rapidly interrupting the light film, thereby interrupting the output of the photo-electric cell. These interruptions appear as sound waves from the loud speaker.

651. R. C. A. Photophone system: In the R. C. A. Photophone system, the recording is accomplished by an oscillograph whose mirror is actuated by the variations in the frequency and intensity of the output voltage of the photoelectric cell, so as to throw a strong beam of light on to a moving film. These light variations, corresponding to sound variations, are recorded as a single jagged, heavy line that looks like a succession of mountain peaks viewed from a distance.

Fig. 507 shows the combined picture and sound projector. In this, as in the Movietone, the light beam passes through the sound-track on the

film, on to a photoelectric cell. In this cell, the varying light gives rise to feeble variations of electric currents which are greatly magnified by the amplifier, so as to operate a number of loud speakers on the stage. The machine is usually provided with an attachment whereby either the variable density (Movietone) film or the disc records (Vitaphone) may also be reproduced as sound.

652. Splicing film: In case the film which is synchronized with the sound from a separate disc-record becomes broken, it is necessary to



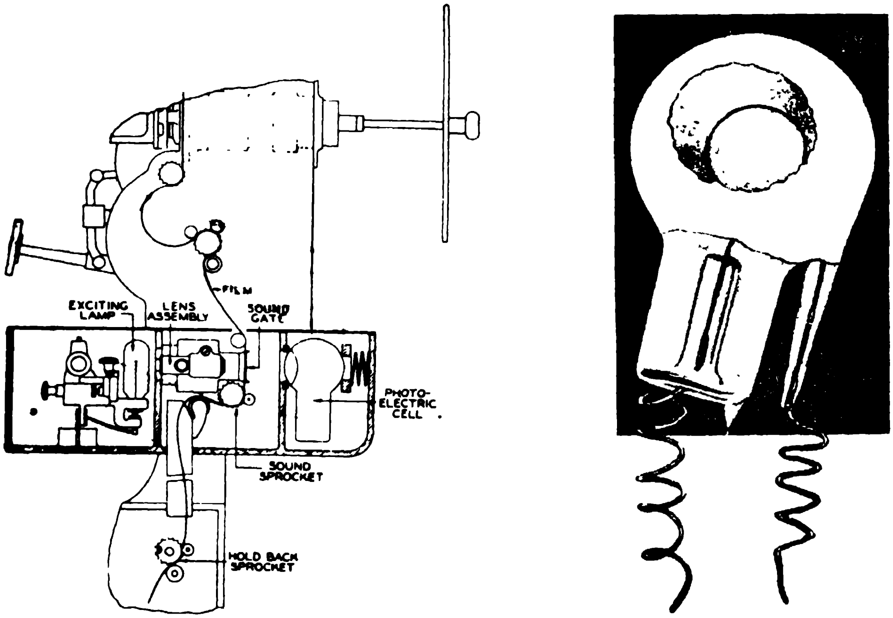
Courtesy Electrical Research Products Corp.

Fig. 504—An interior view of a typical sound head on a motion picture projector. The exciting lamp and control rheostat are in the compartment at the left. The condenser lens system is in the center compartment. The film also comes down through this compartment. The photoelectric cell (see Fig. 505) is in the compartment at the right. It is held between two thick pieces of sponge rubber by the coiled spring shown. See left of Fig. 505.

splice in a length of blank film equal to the length of film removed due to the break, in order to prevent the sound from getting out of synchronism with the picture.

In case a film which has the sound track on it becomes broken, the splice must be made in a special way in order to prevent a loud thump

from being heard from the horns when the splice passes through the sound gate. This "thump" would be caused by the electrical impulses sent into the amplifier by any discontinuity which was present in the sound track.



Courtesy Bell Laboratories

Fig. 505—Left: Simplified diagram showing the arrangement of the apparatus in the sound head of a motion picture projector equipped to reproduce from sound-on-film pictures. (See Fig. 504.)
Right: A photoelectric cell employed in sound-on-film reproducing apparatus. Notice the clear "window" in the glass bulb through which the light may shine on to the sensitized surface inside. The circular-hoop plate is also visible inside. (See right of Fig 504.)

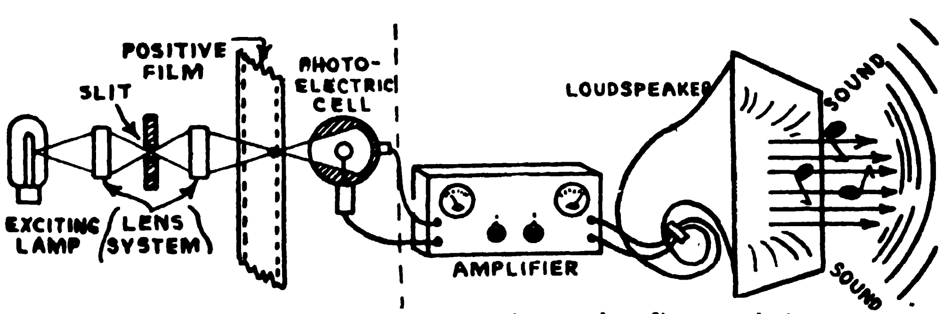


Fig. 506—A simple schematic diagram of the entire sound-on-film reproducing system. The actual apparatus is shown in the accompanying illustrations.

In dealing with a film of this type, the splice is first made in the usual manner. Then it should be painted with black or red lacquer as shown at A of Fig. 508. The painted mark on the sound track should be roughly triangular in shape with a rounded apex. and between ⅜ inches and ½ inches wide at the base. If the splice is painted

in this manner, it will be almost inaudible when passing through the reproducing mechanism, as any change in light intensity which it causes, will be at a low frequency below the audible range. If the base of the triangle is made too short, as shown at "B", the change in light will be abrupt, and the thump produced will be very pronounced. If it is made too long, as shown at "C", enough of the sound track may be obliterated to cause noticeable interruption or pause in the sound. Therefore,

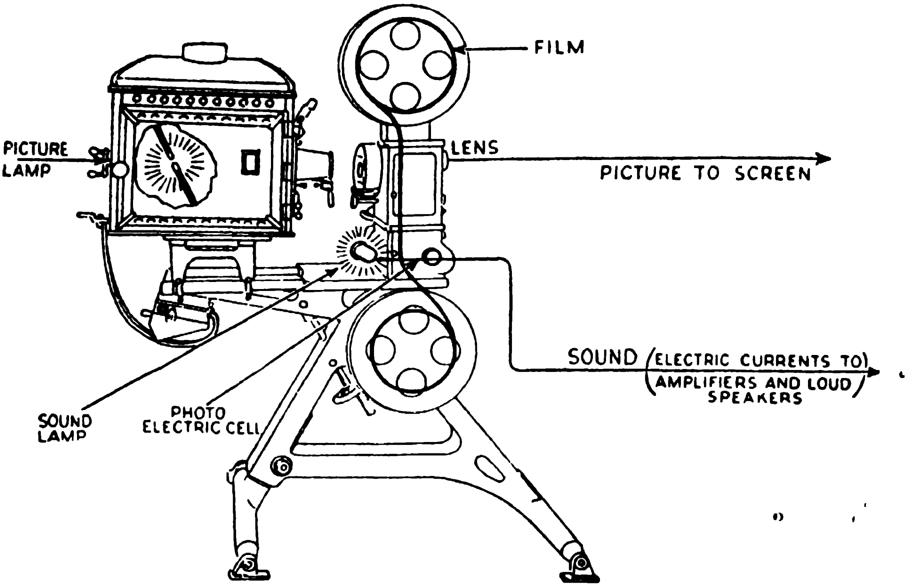


Fig. 507—R C. A Photophone picture projector and sound reproducing equipment! The sound recordings are shown at the right of Fig. 498.

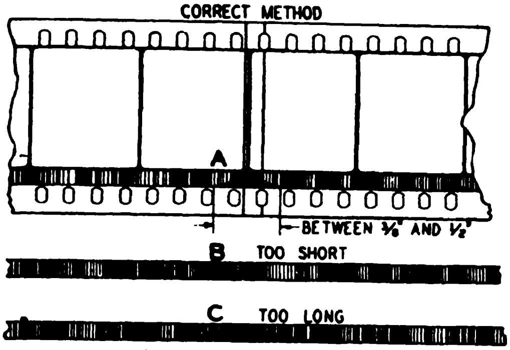
the painting of the triangle should be done with care. It is done on the shiny celluloid side of the film.

653. Comparison of sound-on-disc and sound-on-film systems: While both the sound-on-disc, and sound-on-film systems are being used at the present time, it is probable that the sound-on-disc system will be abandoned in the near future, in favor of the sound-on-film method. The present arrangement of using both systems has many disadvantages, possibly the most important of which is the fact that motion picture exhibitors are forced to install projecting machines equipped both with the turntable and pick-up unit for sound-on-disc films, and the exciting lamp, lens system, photo-electric cell and head amplifier for exhibiting sound-on-film pictures. This greatly adds to the expense and maintenance costs of the projectors.

While each of the systems has certain advantages, it seems probable that the economic disadvantages of the sound-on-disc system film will cause it to be dropped.

In the first place, two discs must be shipped with each reel of film—one disc for the actual playing and one to be used as a spare in case of damage to the first one. This means that the cost of shipping the discs

from theatre to theatre is very high, also since the discs must be shipped in separate containers from those which hold the films, the problem of handling them is quite troublesome. Since, in the sound-on-film system, both the sound track and the picture are on the same film, the shipping of the films is no more expensive than it is with the old silent-type films. One advantage of the sound-on-disc system is that the film which contains the picture can be used much longer than it can in the sound-on-film



Courtesy Electrical Research Prod. Corp.

Fig. 508—How film with a sound track should be spliced. An opaque triangle is painted in on the sound track as shown at A.

system. In the latter the life of the film is determined by the time when the film becomes sufficiently scratched due to running through the projector, so that the sound track becomes very noisy. The entire film must then be scrapped. In the sound-on-disc system, when the disc becomes too noisy due to wear, new duplicate discs are supplied, the same film still being used for the picture.

REVIEW QUESTIONS

1. Describe the sound-on-disc method of recording sound motion pictures.
2. What is the "wax"; the "play-back"?
3. What is the "fader", and what is it used for in sound picture systems?
4. Describe the sound-on-film method of recording.
5. Why are motion picture cameras covered with sound proof enclosures when recording sound pictures?
6. Describe the process of reproduction in the sound-on-disc system.
7. How is synchronization accomplished and maintained between the motion picture projector mechanism and the sound disc in this system?
8. Describe the process of reproduction in the sound-on-film system. How is synchronization accomplished and maintained between the picture on the film, and the sound track during reproduction?

9. What is the function of the photoelectric cell in the sound-on-film reproducing system? Draw a simple schematic sketch showing the relation to the light source, lens system, slit, sound track on the film, amplifier and loud speakers, in the sound-on-disc reproducing system.
10. Describe the loud speakers used in sound picture reproduction. Where are they located, and how are they arranged? Give the reason for the particular location that is employed.
11. How should splices be made in sound-film to avoid objectionable noises?
12. Draw a sketch showing how the sound track on Movietone film appears. How are the darkness of the lines of the track, and the number of lines per inch, related to the sounds?
13. Draw a sketch showing the sound track on the film used in the Photophone system. Explain what features of this sound track are responsible for the variations in frequency and the variations in loudness of the sound produced.
14. Draw a schematic sketch showing the light source, condensing lens, light valve, objective lens and film used in the recording of the sound track in sound-on-film pictures. Explain the function of each part, and explain how the light valve operates.
15. What is the difference in the recording methods used for recording the sound track in the studio, and those used in recording the sound track for news reels, travel pictures, etc.?

APPENDIX A

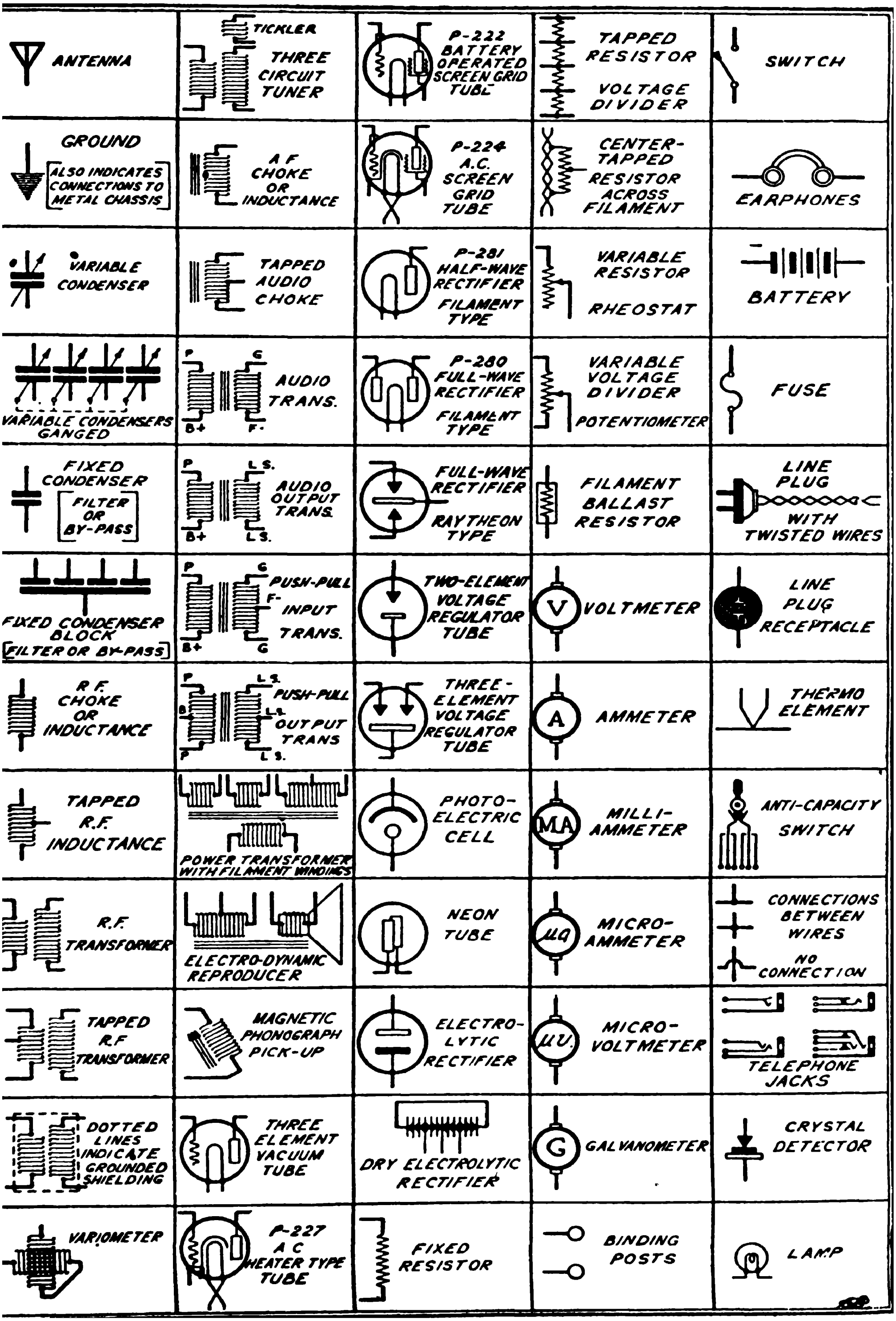
RADIO SYMBOLS

The tremendous growth of the radio art has resulted in the invention of many new electrical devices unknown a few years ago. These, together with such well known things as coils, condensers, resistors, etc., make the total number of different parts used in radio receivers very large.

In order to represent these pieces of equipment in their proper relation in drawings and circuit diagrams, conventional graphical symbols have been devised. It is unfortunate that no absolute standardization of radio symbols has been accepted in radio work up to the present time (even though the R.M.A. has adopted a standard set of radio symbols) but the following chart contains most of the symbols which have become well known through more or less popular usage. In those cases where more than one symbol is commonly used for a piece of equipment, the several symbols are given.

These symbols have been used throughout this book, so it would be well for the reader to thoroughly acquaint himself with them, in order that he may quickly and thoroughly understand the diagrams. It must be remembered that radio transmitters and receivers are built up of many component parts or units. So, the circuit diagrams are also built up by properly connecting up many of these symbols together. It is suggested that the reader select some circuit diagrams in this book and see if he can name all of the parts shown. Then he should attempt to re-draw the circuits himself, using the proper symbols. This practice is very necessary in order to remember the symbols, and to become proficient in drawing and tracing out circuits for which no diagrams may be available.

(See Chart on Next Page)


ANTENNA
TICKLER
THREE CIRCUIT TUNER
P-222 BATTERY OPERATED SCREEN GRID TUBE
TAPPED RESISTOR
VOLTAGE DIVIDER
SWITCH
GROUND
ALSO INDICATES CONNECTIONS TO METAL CHASSIS
A F CHOKE OR INDUCTANCE
P-224 A.C. SCREEN GRID TUBE
CENTER-TAPPED RESISTOR ACROSS FILAMENT
EARPHONES
VARIABLE CONDENSER
TAPPED AUDIO CHOKE
P-281 HALF-WAVE RECTIFIER
FILAMENT TYPE
VARIABLE RESISTOR
RHEOSTAT
BATTERY
VARIABLE CONDENSERS GANGED
P
G
AUDIO TRANS.
B+
F-
P-280 FULL-WAVE RECTIFIER
FILAMENT TYPE
VARIABLE VOLTAGE DIVIDER
POTENTIOMETER
FUSE
FIXED CONDENSER
FILTER OR BY-PASS
P
L.S.
AUDIO OUTPUT TRANS.
B+
L.S.
FULL-WAVE RECTIFIER
RAYTHEON TYPE
FILAMENT BALLAST RESISTOR
LINE PLUG
WITH TWISTED WIRES
FIXED CONDENSER BLOCK
FILTER OR BY-PASS
P
G
PUSH-PULL
F-
INPUT
TRANS.
B+
G
TWO-ELEMENT VOLTAGE REGULATOR TUBE
V
VOLTMETER
LINE PLUG RECEPTACLE
R.F. CHOKE OR INDUCTANCE
P
L.S.
PUSH-PULL
B
L.S.
OUTPUT TRANS
P
L.S.
THREE-ELEMENT VOLTAGE REGULATOR TUBE
A
AMMETER
THERMO ELEMENT
TAPPED R.F. INDUCTANCE
POWER TRANSFORMER WITH FILAMENT WINDINGS
PHOTO-ELECTRIC CELL
MA
MILLI-AMMETER
ANTI-CAPACITY SWITCH
R.F. TRANSFORMER
ELECTRO-DYNAMIC REPRODUCER
NEON TUBE
μa
MICRO-AMMETER
CONNECTIONS BETWEEN WIRES
NO CONNECTION
TAPPED R.F TRANSFORMER
MAGNETIC PHONOGRAPH PICK-UP
ELECTRO-LYTIC RECTIFIER
μv
MICRO-VOLTMETER
TELEPHONE JACKS
DOTTED LINES INDICATE GROUNDED SHIELDING
THREE ELEMENT VACUUM TUBE
DRY ELECTROLYTIC RECTIFIER
G
GALVANOMETER
CRYSTAL DETECTOR
VARIOMETER
P-227 A C HEATER TYPE TUBE
FIXED RESISTOR
BINDING POSTS
LAMP

LETTER SYMBOLS AND ABBREVIATIONS

In radio language there are many symbols and abbreviations (short-hand expressions) that make it convenient to express, otherwise long or cumbersome words in a rather short and simple manner. No one can do much in the way of studying radio or electrical diagrams, or reading technical articles without first becoming familiar with the letter symbols and abbreviations in common use. Following is a list of those which have been adopted by the Radio Manufacturers Association (R. M. A.) in the United States. Some of these have international acceptance, some are used only in this country, and some have not been agreed upon generally in practice even in the United States. These abbreviations have been used throughout this book wherever possible, in order to further the cause of a standard simplified practice.

Many of the abbreviations are given in lower-case letters. Where the original word would have been capitalized, the abbreviations should be similarly capitalized. A two-word adjective expression should contain a hyphen. The greek letter μ is sometimes written as "mu".

These abbreviations are published here through the courtesy and co-operation of the Radio Manufacturers Association.

Term	Abbreviation, or letter-symbol.
Alternating-current (adjective)	a-c
Alternating current	spell out.
Ampere	a
Antenna	ant.
Audio-frequency (adjective)	a-f
Continuous waves	CW
Cycles per second	~
Decibel	db
Direct-current (adjective)	d-c
Direct-current	spell out.
Electromotive force	e.m.f.
Frequency	f
Ground	Gnd.
Henry	h
Intermediate-frequency (adjective)	i-f
Interrupted continuous waves	ICW
Kilocycles (per second)	kc
Kilowatt	kw
Megohm	M Ω
Microfarad	μf
Microhenry	μh
Micromicrofarad (pico-farad)	μμf

(Continued on next page)

APPENDIX B—Cont'd.

Term	Abbreviation, or letter-symbol.
Microvolt	μv
Microvolt per meter	$\mu v/m$
Millivolt per meter	mv/m
Milliwatt	mw
Ohm	Ω
Power Factor	p.f.
Radio-Frequency (adjective)	r-f
Volt	v

LETTER SYMBOLS—VACUUM TUBE NOTATION

The accepted R. M. A. System of notation of terms used in connection with vacuum tube nomenclature follows. The small letter "r" is used for resistance. Thus r_p indicates the plate resistance of a vacuum tube. The letter p is called a subscript and states that "r" in this case is a particular resistance, namely, the resistance of the plate circuit of a vacuum tube.

In a similar manner, subscripts are used on the letters E, I, etc. denoting voltages and currents, to form E_p, E_g, E_f for the plate, grid and filament voltages of a vacuum tube, and I_p, I_g and I_f to indicate the plate, grid, and filament currents. When current, voltage, and power vary with time, lower-case italics are used for instantaneous values, and capital italics for constant values.. The root-mean-square value is designated by capitals. The letter g is the symbol for conductance. Thus, the mutual conductance of a vacuum tube is g_m.

Quantity	Symbol
Grid potential	E_g, e_g
Grid current	I_g, i_g
Grid conductance	g_g
Grid resistance	$r_g = \dfrac{1}{g_g}$
Grid bias voltage	E_c
Plate potential	E_p, e_p
Plate current	I_p, i_p
Plate conductance	g_p
Plate resistance	$r_p = \dfrac{1}{g_p}$
Plate supply voltage	E_b
Emission current	I_s
Mutual conductance	g_m

Quantity	Symbol
Amplification factor	$\mu(\text{mu}) = \dfrac{g_m}{g_p}$
Filament terminal voltage	E_f
Filament current	I_f
Filament supply voltage	E_a
Grid-plate capacity	C_{gp}
Grid-filament capacity	C_{gf}
Plate-filament capacity	C_{pf}
Grid capacity	$C_g = C_{gp} + C_{gf}$
Plate capacity	$C_p = C_{gp} + C_{pf}$
Filament capacity	$C_f = C_{gf} + C_{pf}$

Although at first glance the abbreviation system may look complicated, it is in reality a simple and logical system, and one with which it is important to be familiar. The majority of the symbols used in radio work belong to electrical terminology established years ago. They have been carried over to similar application in radio work.

APPENDIX C

METRIC PREFIXES USED IN RADIO WORK

It so happens that many of the units used extensively in electrical work are either too small or too large for convenient expression or use in radio work. Instead of using large, cumbersome numbers to indicate the fractional or multiple parts of these units, it has become customary to make use of standard metric prefixes ahead of the standard units to simplify expressions and calculations involving these quantities. These metric prefixes are so commonly used in radio work that the service man should familiarize himself with them, so that he may become proficient in understanding and using them. A list of these prefixes is given below:

Prefix	*Abbreviation*	*Meaning*
deci	*d*	one-tenth part of
centi	*c*	one hundredth part of
mil or *milli*	*m*	one-thousandth part of
micro	μ	one-millionth part of
pica or *micro-micro*	μμ or *mm*	one-millionth of a millionth part of
deka	*dk*	10 times
hekto	*h*	100 times
kilo	*k*	1,000 times
mega	*M*	1,000,000 times

Thus, *deci*, means that the new unit is 0.1 of the standard unit. A *decimeter* is 0.1 of a meter. A *milliampere* is 0.001 of an ampere. A *microhenry* is 0.000001 of a henry. A *microfarad* is 0.000001 of a farad. Instead of saying that a condenser has a capacity of 0.00035 microfarads, we can say that it has a capacity of 350 micro-microfarads, etc.

A *centimeter* of inductance is equal to 0.001 of a microhenry. This unit does not follow the general rule.

The prefix *deka* means that the new unit is ten times the standard unit. The prefix *kilo* means that the new unit is 1,000 times the standard unit. Thus, one *kilocycle* equals 1,000 cycles. The prefix *meg* or *mega* means that the new unit is 1,000,000 times the original unit. Thus, one *megohm* equals 1,000,000 ohms, etc.

The word microfarad used in general radio work as a unit of capacitance has several notations for its abbreviation now in common use. According to the above list of prefixes, microfarad should be abbreviated μf but other notations such as mfd. and mf. are also firmly entrenched in the minds of radio men and are used extensively by condenser manufacturers for marking condensers.

(Continued on next page)

CONVERSION OF UNITS EXPRESSED WITH METRIC PREFIXES

As it is often very difficult for persons inexperienced in the handling of mathematical computations to correctly convert from one form into another the various electrical units which are expressed with the common metric prefixes, the following factors for conversion have been arranged alphabetically here to assist the student in this work.

Multiply	*By*	*To Convert To:*
Amperes	× 1,000,000,000,000	micromicroamperes
Amperes	× 1,000,000	microamperes
Amperes	× 1,000	milliamperes
Cycles	× .000,001	megacycles
Cycles	× .001	kilocycles
Farads	× 1,000,000,000,000	micromicrofarads or picofarads
Farads	× 1,000,000	microfarads
Farads	× 1,000	millifarads
Henries	× 1,000,000	microhenries
Henries	× 1,000	millihenries
Horsepower	× .7457	kilowatts
Horsepower	× 745.7	watts
Kilocycles	× 1,000	cycles
Kilovolts	× 1,000	volts
Kilowatts	× 1,000	watts
Kilowatts	× 1.341	horsepower
Megacycles	× 1,000,000	cycles
Mhos	× 1,000,000	micromhos
Mhos	× 1,000	millimhos
Microamperes	× .000,001	amperes
Microfarads	× .000,001	farads
Microhenries	× .000,001	henrys
Micromhos	× .000,001	mhos
Micro-ohms	× .000,001	ohms
Microvolts	× .000,001	volts
Microwatts	× .000,001	watts
Micromicrofarads	× .000,000,000,001	farads
Micromicro-ohms	× .000,000,000,001	ohms
Milliamperes	× .001	amperes
Millihenries	× .001	henrys
Millimhos	× .001	mhos
Milliohms	× .001	ohms
Millivolts	× .001	volts
Milliwatts	× .001	watts
Ohms	× 1,000,000,000,000	micromicro-ohms
Ohms	× 1,000,000	micro-ohms
Ohms	× 1,000	milliohms
Volts	× 1,000,000	microvolts
Volts	× 1,000	millivolts
Watts	× 1,000,000	microwatts
Watts	× 1,000	milliwatts
Watts	× .001	kilowatts

APPENDIX D

THE USE OF EXPONENTS IN CALCULATIONS

It is very convenient to express very large or very small quantities by means of whole numbers with suitable exponents. For instance, the rather cumbersome number 350,000,000 may be written as 3.5×10^8, which really means that 3.5 is multiplied by *ten*, eight times. The small number above, and to the side of the figure 10 is called the *exponent*. In this case the exponent is 8. Numbers less than 1 have *negative* exponents. Thus five ten-thousandths may be expressed in the following ways.

$$.0005 \text{ or } 5 \times 10^{-4}, \text{ or } \frac{5}{10{,}000} \text{ or } \frac{5}{10^4}.$$

This representation is really a shorthand method of working with inconveniently large or small quantities, and the student should become thoroughly familiar with it, as it is used extensively in technical work. The table below will be found helpful in understanding how the proper exponent is found.

$$\begin{aligned} 1 &= 10^0 = \text{Units} \\ 10 &= 10^1 = \text{Tens} \\ 100 &= 10^2 = \text{Hundreds} \\ 1{,}000 &= 10^3 = \text{Thousands } (\textit{Kilo.}) \\ 1{,}000{,}000 &= 10^6 = \text{Millions } (\textit{Mega.}) \end{aligned}$$

$$\begin{aligned} 1 &= 10^0 = \text{Units} \\ .1 &= 10^{-1} = \text{Tenths} \\ .01 &= 10^{-2} = \text{Hundredths} \\ .001 &= 10^{-3} = \text{Thousandths } (\textit{Milli.}) \\ .000001 &= 10^{-6} = \text{Millionths } (\textit{Micro.}) \end{aligned}$$

The rules dealing with these complicated looking figures are simple, and, when mastered, provide an exceptionally easy method of handling large numbers. The rules are as follows:

When multiplying numbers, *add* the exponents.
When dividing numbers, *subtract* the exponents.
When squaring a number, *double* its exponent.
When obtaining a square root, *halve* the exponent.
When transfering an exponent across the dividing line, *change its sign.*

Example: Express the following quantities in simple numbers by the use of exponents. (*a*) 342,000,000,000 (*b*) 9,653,000 (*c*) 0.0000084 (*d*) 0.000432.

Answers: (*a*) 3.42×10^{11} (*b*) 9.653×10^6 (*c*) 8.4×10^{-6} (*d*) 4.32×10^{-4}. *Ans.*

Example: 6.28×10^{18} electrons flowing past a given point in a second constitute a current of 1 ampere. How many electrons flow past a given point in a second when the number of amperes is (*a*) 600? (*b*) 0.002?

Solutions: (*a*) $6.28 \times 10^{18} \times 6 \times 10^2 = 37.68 \times 10^{20}$ or 3.768×10^{21}. *Ans.*
(*b*) $6.28 \times 10^{18} \times 2 \times 10^{-3} = 12.56 \times 10^{15}$ or 1.256×10^{16}. *Ans.*

SUMMARY OF FORMULAE COMMONLY USED IN RADIO WORK

(Formula numbers refer to numbers used in text)

Voltage, Current, Resistance

$$\text{Amperes} = \frac{\text{Volts}}{\text{Ohms}} \qquad \left(I = \frac{E}{R}\right) \tag{1}$$

$$\text{Volts} = \text{Amperes} \times \text{Ohms} \qquad (E = I \times R) \tag{2}$$

$$\text{Ohms} = \frac{\text{Volts}}{\text{Amperes}} \qquad \left(R = \frac{E}{I}\right) \tag{3}$$

Power: $$\text{Watts} = \text{Volts} \times \text{Amperes} \qquad (W = E \times I) \tag{4}$$

$$\text{Watts} = \text{Volts squared divided by ohms} \left(W = \frac{E^2}{R}\right) \tag{5}$$

$$\text{Watts} = \text{Amperes squared} \times \text{ohms} \qquad (W = I^2 R) \tag{6}$$

Resistance: $$R = \frac{kL}{CM} \tag{7}$$

Resistance: $$R = \frac{kL}{CM}\left[1 \pm (a \times t)\right] \tag{8}$$

Resistances in Series: (all resistances in same units)

R is total resistance; r_1, r_2, r_3, etc., are individual resistances.

$$R = r_1 + r_2 + r_3 + \text{etc.} \tag{9}$$

Resistances in Parallel: (all resistances must be in same units)

$$\frac{1}{R} = \frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \text{etc.} \tag{10}$$

or $$R = \frac{1}{\frac{1}{r_1} + \frac{1}{r_2} + \frac{1}{r_3} + \text{etc.}}$$

$$F = \frac{m\, m^1}{d^2} \tag{11}$$

$$L = 0.0251\, d^2\, n^2\, l\, K \tag{12}$$

Capacity of a Condenser:

$$C = \frac{2235\ (N-1)\ A\ k}{10^{10}\ t} \tag{13}$$

Capacity of Condensers in Parallel: (all capacities must be in same units)

$$C = c_1 + c_2 + c_3 + \text{etc.} \tag{14}$$

Capacity of Condensers in Series: (all capacities must be in same units)

$$\frac{1}{C} = \frac{1}{c_1} + \frac{1}{c_2} + \frac{1}{c_3} + \text{etc.} \tag{15}$$

APPENDIX E—Cont'd.

$$\text{or}\quad C=\frac{1}{\frac{1}{c_1}+\frac{1}{c_2}+\frac{1}{c_3}+\text{etc.}}$$

Inductive reactance: $X_L=2\pi fL$ (16)

Capacity reactance: $X_c=\frac{1}{2\pi fC}$ (17)

Impedance (Z) of A.C. Circuit Containing Inductance (L), Capacity (C) and Resistance (R). (frequency f).

$$Z=\sqrt{R^2+X^2}=\sqrt{R^2+\left(2\times 3.1416\times f\times L-\frac{1}{2\times 3.1416\times f\times C}\right)^2} \quad (18)$$

$$I=\frac{E}{\sqrt{R^2+\left(2\pi fL-\frac{1}{2\pi fC}\right)^2}} \quad (19)$$

$$f=\frac{1}{2\pi\sqrt{LC}} \quad (20)$$

Frequency and Wavelength Relations for radio (not for sound)

$$\text{Meters (wavelength)}=\frac{300{,}000{,}000}{\text{cycles}} \quad (21)$$

$$\text{Frequency (Cycles)}=\frac{300{,}000{,}000}{\text{meters (wavelength)}} \quad (22)$$

$$\text{Frequency (Kilocycles)}=\frac{300{,}000}{\text{meters (wavelength)}} \quad (23)$$

Wavelength at which resonance in a series tuned circuit takes place with given inductance (L) and capacity (C)

$$\text{Meters (wavelength)}=1885\sqrt{L\text{ (microhenries)}\times C\text{ (microfarads)}} \quad (24)$$

$$\text{Meters (wavelength)}=1.885\sqrt{L\text{ (microhenries)}\times C\text{ (micro-microfarads)}} \quad (25)$$

Frequency at which resonance takes place with given constants of inductance and capacity.

$$\text{Frequency (Cycles)}=\frac{159{,}000}{\sqrt{L\text{ (microhenries)}\times C\text{ (microfarads)}}} \quad (26)$$

$$\text{Frequency (Cycles)}=\frac{159{,}000{,}000}{\sqrt{L\text{ (microhenries)}\times C\text{ (micro-microfarads)}}} \quad (27)$$

Inductance of a single-layer Inductor: $L=0.0251\,d^2\,n^2\,l\,K$ (28)

$$\text{Loud Speaker Baffle length (in feet)}=\frac{282}{\text{frequency}} \quad (29)$$

WIRE TABLES

In design, construction, or repair work on electrical or radio apparatus, it is very helpful to have at hand complete data on the various types of magnet wire used for winding inductors, transformers, loud speaker coils, etc. It is often very helpful to know just how many turns of wire of a certain size can be wound into a certain available space, what the resistance-per-foot, or the feet-per-ohm, of the wire is, etc. In the case of repair work, it is usually easy to rewind a damaged coil with wire of the same size and type as was on it previously, but when new apparatus is designed it is necessary to refer to tables of wire data for this information.

The reader is urged to familiarize himself with the contents of these tables, for he will find that they will will prove to be real time-savers for him.

TABLE NO. 1

THICKNESS OF COTTON AND SILK INSULATION ON MAGNET WIRE

Wire Size	Thickness of Insulation in Mils (1 Mil = .001 inch)				
B & S	S.C.C.	D.C.C.	T.C.C.	S.S.C.	D.S.C.
0000-5	4.5	9.0	13.5	1.0	2.0
6-7	4.0	8.0	12.0	1.0	2.0
8	3.5	7.0	10.5	1.0	2.0
9	3.0	6.0	9.0	1.0	2.0
10-12	2.5	5.0	7.5	1.0	2.0
13-19	2.25	4 5	7.75	1.0	2.0
13-32	2.5	4.5	7.0	1.0	2.0
14-15	3.0	5.0	7.0	—	—
16-18	2.5	4.0	—	—	—
19-22	2.0	4.0	—	—	—
23-25	2.0	4.0	—	1.5	3.0
20-40	2.0	4.0	6.0	1.0	2.0
26-28	2.0	4.0	—	1.5	3.0
29-34	2.0	4.0	—	1.2	2.5
32-36	—	—	—	0.87	1.75
35-40	2.0	4.0	—	1.0	2.0

(Continued on next page)

APPENDIX F—Cont'd.

BARE COPPER WIRE TABLE

TABLE NO. 2

Giving Measurements at 68° F. (20° C.) with Specific Gravity of 8.89
(Brown & Sharpe)

A. W. G. B. & S. Gauge	Diameter Inches	Area Circular Mils	Weight Pounds per 1000 Feet	Length Feet per Pound	RESISTANCE Ohms per 1000 Feet	RESISTANCE Ohms per Pound
0000	0.4600	211,600.	640.5	1.561	0.04901	.00007652
000	0.4096	167,800.	507.9	1.969	.06180	.0001217
00	0.3648	133,100.	402.8	2.483	.07793	.0001935
0	0.3249	105,500.	319.5	3.130	.09827	.0003076
1	0.2893	83,690.	253.3	3.948	.1239	.0004891
2	0.2576	66,370.	200.9	4.978	.1563	.0007778
3	0.2294	52,630.	159.3	6.276	.1970	.001237
4	0.2043	41,740.	126.4	7.911	.2485	.001966
5	0.1819	33,100.	100.2	9.980	.3133	.003127
6	0.1620	26,250.	79.46	12.58	.3951	.004972
7	0.1443	20,820.	63.02	15.87	.4982	.007905
8	0.1285	16,510.	49.98	20.01	.6282	.01257
9	0.1144	13,090.	39.63	25.23	.7921	.01999
10	0.1019	10,380.	31.43	31.82	.9989	.03178
11	0.09074	8,234.	24.92	40.13	1.260	.05053
12	0.08081	6,530.	19.77	50.58	1.588	.08035
13	0.07196	5,178.	15.68	63.77	2.003	.1278
14	0.06408	4,107.	12.43	80.45	2.525	.2032
15	0.05707	3,257.	9.858	101.4	3.184	.3230
16	0.05082	2,583.	7.818	127.9	4.016	.5136
17	0.04526	2,048.	6.200	161.3	5.064	.8167
18	0.04030	1,624.	4.917	203.4	6.385	1.299
19	0.03589	1,288.	3.899	265.5	8.051	2.065
20	0.03196	1,022.	3.092	323.4	10.15	3.283
21	0.02846	810.1	2.452	407.8	12.80	5.221
22	0.02535	642.4	1.945	514.1	16.14	8.301
23	0.02257	509.5	1.542	648.5	20.36	13.20
24	0.02010	404.0	1.223	817.7	25.67	20.99
25	0.01790	320.4	0.9699	1,031.	32.37	33.37
26	0.01594	254.1	0.7692	1,300.	40.81	53.06
27	0.01420	201.5	0.6100	1,639.	51.47	84.37
28	0.01264	159.8	0.4837	2,067.	64.90	134.2
29	0.01126	126.7	0.3836	2,606.	81.83	213.3
30	0.01003	100.5	0.3042	3,287.	103.2	329.2
31	0.008928	79.70	0.2413	4,144.	130.1	539.3
32	0.007950	63.21	0.1913	5,227.	164.1	857.6
33	0.007080	50.13	0.1517	6,591.	206.9	1,364.
34	0.006305	39.75	0.1203	8,312.	260.9	2,168.
35	0.005615	31.52	0.09542	10,480.	329.0	3,448.
36	0.005000	25.00	0.07568	13,213.	414.8	5,482.
37	0.004453	19.83	0.0601	16,664.	523.1	8,717.
38	0.003965	15.72	0.04759	21,012.	659.6	13,860.
39	0.003531	12.47	0.03774	26,497.	831.8	22,040.
40	0.003145	9.888	0.02990	33,411.	1049.	35,040.
41	0.00275	7.5625	0.02289	43,700.	1370.	59,900.
42	0.00250	6.2500	0.01892	52,800.	1660.	87,700.
43	0.00225	5.0625	0.01532	65,300.	2050.	133,700.
44	0.00200	4.0000	0.01211	82,600.	2600.	214,000.
45	0.00175	3.0625	0.00927	107,900.	3390.	365.200.
46	0.00150	2.2500	0.00681	146,800.	4610.	676,800.

Note: A mil is 1/1000 (one-thousandth) of an inch
Dia. in mils equals dia. in inches × 1000

PROPERTIES OF METALS

The following table, which is published here through the courtesy of the United States Bureau of Standards, gives several of the important physical and electrical characteristics of the common metals and alloys used in industry. For instance, a glance at the column of temperature coefficients of resistance shows that the alloys Therlo, Constantin, and Manganin have the lowest values (.00001). It is for this reason that they are used for shunts and resistances in electrical instruments and for precision resistors, in which it is necessary that the resistance value remain absolutely constant even though the temperature change slightly due to weather changes or to the heat developed by the electric current flowing through them.

A glance at the column of melting points reveals that tungsten has the highest melting point (3000° C.). That is why tungsten is used for the filaments of vacuum tubes and incandescent lamps. Many other interesting facts can be found from a study of this table of the properties of metals.

(See table on next page)

PROPERTIES OF METALS

Metal	Temperature coefficient at 20° C	Specific gravity	Tensile strength lbs./in.^{2}	Melting point, °C
Advance. See Constantin				
Aluminum	0.0039	2.70	30,000	659
Antimony	.0036	6.6		630
Bismuth	.004	9.8		271
Brass	.002	8.6	70,000	900
Cadmium	.0038	8.6		321
Calido. See Nichrome.				
Climax	.0007	8.1	150,000	1250
Constantin	.00001	8.9	120,000	1190
Copper, annealed	.00393	8.89	30,000	1083
Copper, hard-drawn	.00382	8.89	60,000	
Eureka. See Constantin				
Excello	.00016	8.9	95,000	1500
German silver, (18% nickel)	.0004	8.4	150,000	1100
German silver, (30% nickel) See Constantin.				
Gold	.00342	19.3	20,000	1063
Ia Ia. See Constantin.				
Ideal. See Constantin.				
Iron, 99.98 per cent pure	.0050	7.8		1530
Iron. See Steel.				
Lead	.0039	11.4	3,000	327
Magnesium	.004	1.74	33,000	651
Manganin	.00001	8.4	150,000	910
Mercury	.00089	13.546	0	—38.9
Molybdenum, drawn	.004	9.0		2500
Monel metal	.0020	8.9	160,000	1300
Nichrome	.0004	8.2	150,000	1500
Nickel	.006	8.9	120,000	1452
Palladium	.0033	12.2	39,000	1550
Phosphor bronze	.0018	8.9	25,000	750
Platinum	.003	21.4	50,000	1755
Silver	.0038	10.5	42,000	960
Steel, E. B. B.	.005	7.7	53,000	1510
Steel, B. B.	.004	7.7	58,000	1510
Steel, Siemens-Martin	.003	7.7	100,000	1510
Steel, manganese	.001	7.5	230,000	1260
Superior. See Climax				
Tantalum	.0031	16.6		2850
Therlo	.00001	8.2		
Tin	.0042	7.3	4,000	232
Tungsten, drawn	.0045	19	500,000	3000
Zinc	.0037	7.1	10,000	419

Note: See also the tables in Arts. 27, 29 and 48.

DRILL & TAP SIZES

In the construction of radio and electrical equipment, it is necessary to drill and tap holes in various kinds of metals and insulating materials for the machine screws which hold the parts together. Various sizes of machine screws are used in radio work, the most common being the 6x32 (number 6 screw with 32 threads per inch), and the 8x32. The following table shows the screw numbers, the number of threads per inch, their diameter, and the drills to be used in making holes either for threading (tapping) or for allowing the screw to slide through the hole freely (clearance). Thus, to tap a hole for a 6x32 screw, first drill the hole with a No. 36 drill. Then tap it with a 6x32 tap. To drill a clearance hole through which a 6x32 screw will slide freely, use the No. 28 clearance size drill

All metal drilling should be done with round twist drills which are obtainable in the sizes designated by numbers as in the table. When drilling brass, aluminum and cast iron, no lubricant is used. When drilling steel, the drill should be lubricated with light machine oil as it enters the hole.

Insulating materials such as Bakelite, Formica, Celoron, hard rubber, fibre, etc. should be drilled with the point of the drill ground to the usual sixty degree angle but with the front edge of the cutting edge ground straight or flat to remove the hook. Speeds up to 1500 R. P. M. may be used and the drill may be left dry, or lubricated with lard oil or light machine oil. Insulating materials of this kind are rather hard on the drills and dull the points quickly. When the drill comes through the hole in the back it is advisable to hold a block of scrap wood solidly against the surface to prevent the material chipping or breaking through around the edges.

Taps are used for cutting threads on the inside of holes. *Dies* are for threading the outside of rods or screws. The first part of each tap or die number indicates the gauge number of the rod stock from which the screws were cut, or the gauge number of the rod to be threaded, respectively. The second part of each number indicates the number of threads per inch.

SIZES OF TAP* AND CLEARANCE DRILLS

Screw No.	Th'ds Per Inch	Tap Size	Drill Number For Tap	Drill Number Clearance	Screw No.	Th'ds Per Inch	Tap Size	Drill Number For Tap	Drill Number Clearance
2	48	2x48	No. 50	No. 44	8	24	8x24	30	17
2	56	2x56	50	44	8	32	8x32	29	19
2	64	2x64	50	44	10	24	10x24	25	10
3	40	3x40	47	39	10	30	10x30	22	10
3	48	3x48	47	39	10	32	10x32	21	10
3	56	3x56	45	39	12	20	12x20	19	2
4	32	4x32	45	31	12	24	12x24	16	2
4	36	4x36	44	31	12	28	12x28	14	2
4	40	4x40	43	31	14	20	14x20	10	¼
6	32	6x32	36	28	14	24	14x24	7	¼
6	36	6x36	34	28					

*Note: These are the drill sizes for average use. The size drill to use really varies somewhat with the material being drilled.

APPENDIX I

INDUCTANCE $\times$ CAPACITANCE (LC) VALVES

The formula for determining the frequency to which any circuit containing inductance and capacity will tune is:

$$f = \frac{159{,}000}{\sqrt{L \times C}} \text{—or, } Wavelength = 1885\sqrt{L \times C}$$

where, f=the frequency in cycles per second
L=the inductance of the coil in microhenries
C=the capacity of the entire circuit in microfarads.

The product of the inductance L and the capacity C of the circuit determines the frequency at which the circuit is resonant or in "tune". For each frequency there is a definite value of this product (called the inductance-capacity product, or the "$L \times C$" value) for which resonance occurs. If this value is known, it is possible to determine the correct amount of inductance required for use with any value of capacity, or the correct amount of capacity for use with any value of inductance, to produce resonance at that frequency. The $L \times C$ value is divided by the known capacity, or the known inductance, the quotient of the division being the required inductance or capacitance. Thus:

$$\text{Inductance} = \frac{L \times C \text{ value}}{\text{capacity}} \qquad \text{Capacity} = \frac{L \times C \text{ value}}{\text{inductance}}$$

The following table gives the inductance-capacity values necessary to produce resonance at frequencies from 1 to 39,000 meters. The inductance is in microhenries, the capacity is in microfarads, and n is the frequency in cycles per second.

As examples of the use of this table, let it be desired to find the required inductance of a coil to tune to a frequency of 600 kilocycles (500 meters) with a tuning condenser of 0.00035 microfarads maximum capacity. From the table, the $L \times C$ value for this frequency is found to be 0.0704. Dividing this value by the capacity (0.00035) gives the result, 201 microhenries of inductance.

Let is be desired to find the required capacity of this tuning condenser to tune to the frequency of 1500 kilocycles (200 meters) with the above coil of 201 microhenries inductance. The $L \times C$ value for this frequency is found from the table to be 0.01126. Dividing this by the inductance (201) gives as a result 0.000055 microfarads for the minimum capacity. The tuning condenser must then have a range of capacitance from 0.000055 to 0.00035 microfarads to cover this frequency range with this inductor. Any other coil and condenser combination may be calculated in this same way.

Looking at the table we note that, as the frequency decreases, the $L \times C$ constant increases. If we divide the frequency by 10, the $L \times C$ constant must be multiplied by 100. This must be kept in mind if values beyond the ranges of the table are to be determined. For instance, if we wish to determine the $L \times C$ constant for 2 kc (2,000 cycles), we look up the value for (2,000,000 *cycles* on the table) and move the decimal point six places to the right; 6330 is the correct constant. If it is desired to check the results, remember that resonance occurs when the inductive reactance is equal to the capacitive reactance. The frequency at which this occurs is the *resonance* frequency.

RELATION BETWEEN WAVELENGTH IN METERS, FREQUENCY IN KILOCYCLES, AND THE PRODUCT OF INDUCTANCE IN MICROHENRIES, AND CAPACITY IN MICROFARADS, REQUIRED TO PRODUCE RESONANCE AT THESE CORRESPONDING FREQUENCIES OR WAVELENGTHS.

(L x C CONSTANT)

W.L. in Meters	*f* in Kc.	*L* x *C*	W.L. in Meters	*f* in Kc.	*L* x *C*	W.L. in Meters	*f* in Kc.	*L* x *C*
1	300,000	0.0000003	450	667	0.0570	740	405	0.1541
2	150,000	0.0000111	460	652	0.0596	745	403	0.1562
3	100,000	0.0000018	470	639	0.0622	750	400	0.1583
4	75,000	0.0000045	480	625	0.0649	755	397	0.1604
5	60,000	0.0000057	490	612	0.0676	760	395	0.1626
6	50,000	0.0000101	500	600	0.0704	765	392	0.1647
7	42,900	0.0000138	505	594	0.0718	770	390	0.1669
8	37,500	0.0000180	510	588	0.0732	775	387	0.1690
9	33,333	0.0000228	515	583	0.0747	780	385	0.1712
10	30,000	0.0000282	520	577	0.0761	785	382	0.1734
20	15,000	0.0001129	525	572	0.0776	790	380	0.1756
30	10,000	0.0002530	530	566	0.0791	795	377	0.1779
40	7,500	0.0004500	535	561	0.0806	800	375	0.1801
50	6,000	0.0007040	540	556	0.0821	805	373	0.1824
60	5,000	0.0010140	545	551	0.0836	810	370	0.1847
70	4,290	0.0013780	550	546	0.0852	815	368	0.1870
80	3,750	0.0018010	555	541	0.0867	820	366	0.1893
90	3,333	0.0022800	560	536	0.0883	825	364	0.1916
100	3,000	0.00282	565	531	0.0899	830	361	0.1939
110	2,727	0.00341	570	527	0.0915	835	359	0.1962
120	2,500	0.00405	575	522	0.0931	840	357	0.1986
130	2,308	0.00476	580	517	0.0947	845	355	0.201
140	2,143	0.00552	585	513	0.0963	850	353	0.203
150	2,000	0.00633	590	509	0.0980	855	351	0.206
160	1,875	0.00721	595	504	0.0996	860	349	0.208
170	1,764	0.00813	600	500	0.1013	865	347	0.211
180	1,667	0.00912	605	496	0.1030	870	345	0.213
190	1,579	0.01015	610	492	0.1047	875	343	0.216
200	1,500	0.01126	615	488	0.1065	880	341	0.218
210	1,429	0.01241	620	484	0.1082	885	339	0.220
220	1,364	0.01362	625	480	0.1100	890	337	0.223
230	1,304	0.01489	630	476	0.1117	895	335	0.225
240	1,250	0.01621	635	472	0.1135	900	333	0.228
250	1,200	0.01759	640	469	0.1153	905	331	0.231
260	1,154	0.01903	645	465	0.1171	910	330	0.233
270	1,111	0.0205	650	462	0.1189	915	328	0.236
280	1,071	0.0221	655	458	0.1208	920	326	0.238
290	1,034	0.0237	660	455	0.1226	925	324	0.241
300	1,000	0.0253	665	451	0.1245	930	323	0.243
310	968	0.0270	670	448	0.1264	935	321	0.246
320	938	0.0288	675	444	0.1283	940	319	0.249
330	909	0.0306	680	441	0.1302	945	317	0.251
340	883	0.0325	685	438	0.1321	950	316	0.254
350	857	0.0345	690	435	0.1340	955	314	0.257
360	834	0.0365	695	432	0.1360	960	313	0.259
370	811	0.0385	700	429	0.1379	965	311	0.262
380	790	0.0406	705	426	0.1399	970	309	0.265
390	769	0.0428	710	423	0.1419	975	308	0.268
400	750	0.0450	715	420	0.1439	980	306	0.270
410	732	0.0473	720	417	0.1459	985	305	0.273
420	715	0.0496	725	414	0.1479	990	303	0.276
430	698	0.0520	730	411	0.1500	995	302	0.279
440	682	0.0545	735	408	0.1521	1000	300	0.282

APPENDIX J

WAVELENGTH — FREQUENCY CHANNEL CHART

Radio engineers started so long ago to think and calculate in terms of wavelength (meters) that no one remembers just why they started that way. Today, however, with the governments of all countries allocating transmitting stations by definite frequency separations (in kilocycles), it is much more convenient and accurate to work in terms of frequency.

Unfortunately, this new habit is not easy to acquire, because the kilocycle difference per wavelength is very great at short wavelengths (that is, below about 50 meters), and very small at the usual broadcast wavelengths, between 200 and 550 meters.

The relation between frequency and wavelength is this: radio wave disturbances are propagated at the same speed as light, approximately 300,000,000 meters per second. This corresponds to about 186,000 miles per second. If the *wavelength* of a particular transmitting station, for instance, is 100 meters, each wave travels 100 meters before the next one starts. Therefore, during one second there is time for 300,000,000 ÷ 100 = 3,000,000 such waves. Consequently the frequency is 3,000,000 cycles.

$$\text{Frequency (cycles per sec.)} = \frac{300{,}000{,}000}{\text{Wavelength (in meters)}}$$

In general, the frequency as expressed in cycles is a large and unwieldy number, so radio engineers use the term "kilocycle," which stands for one thousand cycles. Thus, instead of saying 1,000,000 cycles (equivalent to 300 meters), we say 1,000 kilocycles. The term is usually abbreviated into the letters "kc." On the very short wavelengths, the frequency runs up into several million cycles, so the term "megacycles," meaning one million cycles, is frequently found to be more convenient than "kilocycles".

Nowadays, we work in terms of frequency rather than wavelength, because it has been found that a uniform 10-kilocycle separation between stations is enough to prevent the transmitters from causing interference with each other in selective receiving sets. There is no way of expressing this separation as a uniform quantity in terms of wavelength. For example, the difference between 590 to 600 meters is approximately 10 kilocycles, while the difference between 10 meters and 20 meters is 15,000 kilocycles.

The chart on a following page discloses one very interesting fact that many people do not appreciate. If we take the range from 200 to 500 meters, for broadcasting, we find it equal to a band 900 kilocycles wide. This means it is big enough to accommodate ninety transmitting bands or "channels" each 10 kilocycles wide. In the space between 10 meters and 200 meters (a band only 190 meters wide compared to 300 meters for the 200-500 range) there is a frequency difference of 28,500 kilocycles, which

will give us 2,850 ten-kilocycle channels. In other words, between 10 and 200 meters there is room for 32 times as many broadcasting stations as between 200 and 500 meters. There is room for even a greater number of code stations, since they do not require as much frequency separation as broadcasting stations. When we consider this, we realize why short waves have assumed such a tremendous commercial importance, with many different communication companies asking for more channels than there are available.

Even though you are not in the habit of thinking in terms of frequency, when you read that the band between 6,000 and 6,150 kilocycles is reserved for shortwave broadcasting you can look at the chart, find 6,000 kc., and, following the line from left to right, see that this refers to a space between 50 meters and about 51 meters. Then you will realize that, although the wavelength separation is only one meter, the band has fifteen 10-kilocycle bands, or room for one-sixth as many stations as can operate between 200 and 500 meters.

Again, the band between 28,000 and 30,000 kc. has been assigned to amateurs and experimenters. Here is a separation of only .7 meters, yet there are two hundred 10kc. bands in what appears to be a very small wavelength range.

(See following page for Chart)

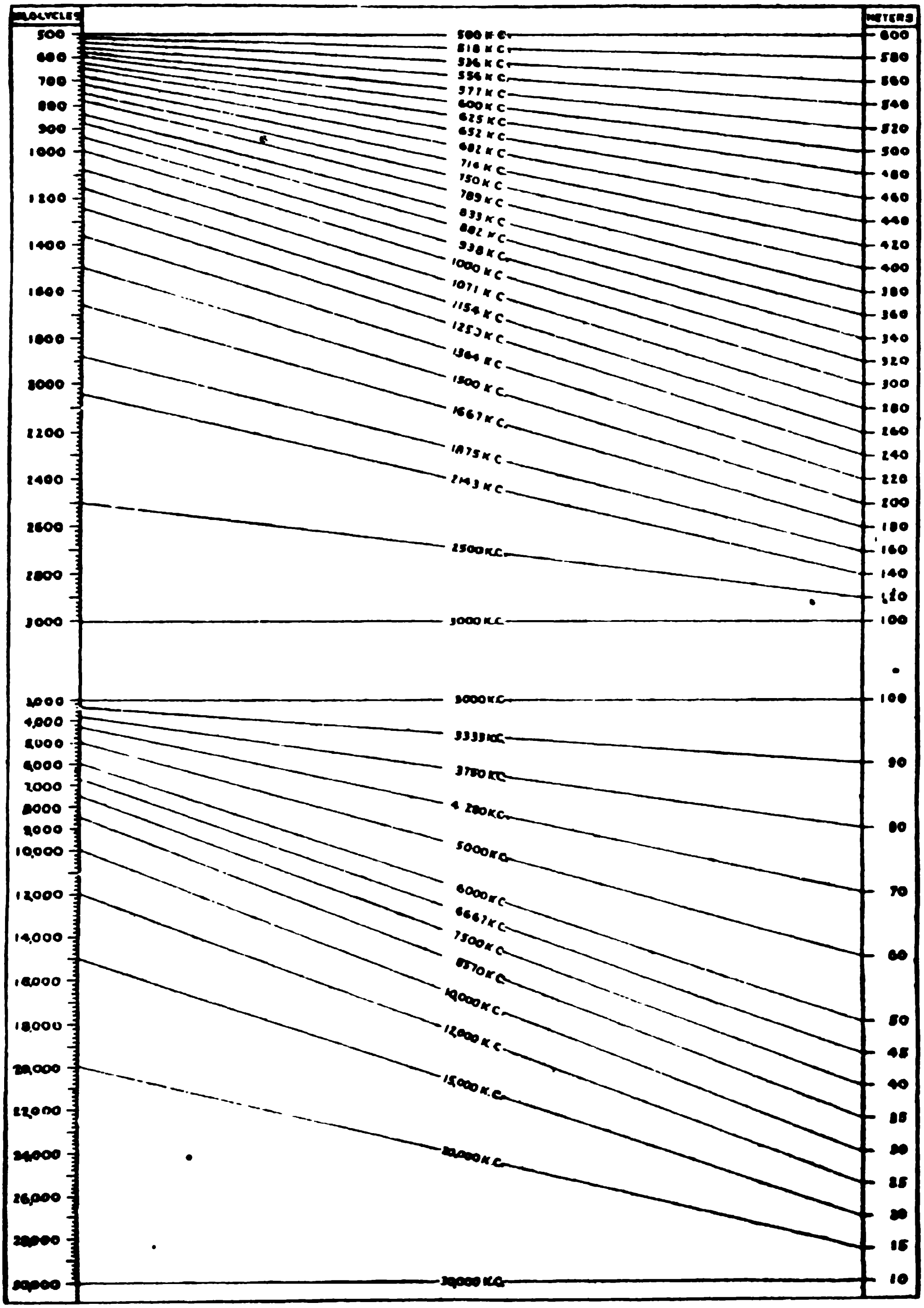


Fig. 510—Wavelength—frequency channel chart.

KILOCYCLE — METER CONVERSION TABLE

There is an increasing tendency in radio practice to think and deal with radio waves in terms of frequencies in kilocycles rather than wavelengths in meters. "Kilo" means a thousand, and "cycle" means one complete alternation. The number of kilocycles (abbreviated kc.) indicates the number of thousands of times that the rapidly alternating current in the antenna repeats its flow in either direction in one second. The smaller is the wave length in meters, the larger is the frequency in kilocycles. The numerical relation between the two is given by the following rule. For approximate calculation, to obtain kilocycles divide 300,000 by the number of meters, and to obtain meters divide 300,000 by the number of kilocycles. For example, 100 meters equals approximately 3,000 kilocycles, 300 m equals 1,000 kc, 1,000 m equals 300 kc, 3,000 m equals 100 kc. For very accurate conversion, the factor 299,820 is used instead of 300,000. This rule is based on the fact that wave length is equal to velocity divided by frequency, and the velocity of radio waves in space according to the best data available is 299,820,000 meters per second.

This table gives accurate values of kilocycles corresponding to any number of meters, and vice versa. It is based on the factor 299,820, and gives values for every 10 kilocycles or meters. It should be particularly noticed that the table is entirely reversible. For example, 50 kilocycles is 5,996 meters, and also, 50 meters is 5,996 kilocycles. The range of the table is easily extended by shifting the decimal point; the shift is in opposite directions for each pair of values; for example, one cannot find 223 in the first column, but its equivalent is obtained by finding later in the table that 2,230 kilocycles or meters is equivalent to 1,344 meters or kilocycles.

It is suggested that the student make frequent use of this table, to accustom himself as quickly as possible to use of the term "kilocycles" in referring to frequencies of stations, although wavelengths or corresponding frequencies can be calculated by the formulas given elsewhere in this book. The use of this table makes the rather laborious calculations unnecessary and insures accuracy of results. The table is reproduced here by the courtesy of the Bureau of Standards.

(See next page for Table)

KILOCYCLES (kc) TO METERS (m), OR METERS TO KILOCYCLES
[Columns Are Interchangeable]

kc or m	m or kc	kc or m	m or kc	kc or m	m or kc	kc or m	m or kc	kc or m	m or kc
10	29,982	510	587.9	1,010	296.9	1,510	198.6	2,010	149.2
20	14,991	520	576.6	1,020	293.9	1,520	197.2	2,020	148.4
30	9,994	530	565.7	1,030	291.1	1,530	196.0	2,030	147.7
40	7,496	540	555.2	1,040	288.3	1,540	194.7	2,040	147.0
50	5,996	550	545.1	1,050	285.5	1,550	193.4	2,050	146.3
60	4,997	560	535.4	1,060	282.8	1,560	192.2	2,060	145.5
70	4,283	570	526.0	1,070	280.2	1,570	191.0	2,070	144.8
80	3,748	580	516.9	1,080	277.6	1,580	189.8	2,080	144.1
90	3,331	590	508.2	1,090	275.1	1,590	188.6	2,090	143.5
100	2,998	600	499.7	1,100	272.6	1,600	187.4	2,100	142.8
110	2,726	610	491.5	1,110	270.1	1,610	186.2	2,110	142.1
120	3,499	620	483.6	1,120	267.7	1,620	185.1	2,120	141.4
130	2,306	630	475.9	1,130	265.3	1,630	183.9	2,130	140.8
140	2,142	640	468.5	1,140	263.0	1,640	182.8	2,140	140.1
150	1,999	650	461.3	1,150	260.7	1,650	181.7	2,150	139.5
160	1,874	660	454.3	1,160	258.5	1,660	180.6	2,160	138.8
170	1,764	670	447.5	1,170	256.3	1,670	179.5	2,170	138.1
180	1,666	680	440.9	1,180	254.1	1,680	178.5	2,180	137.5
190	1,578	690	434.5	1,190	252.0	1,690	177.4	2,190	136.9
200	1,499	700	428.3	1,200	249.9	1,700	176.4	2,200	136.3
210	1,428	710	422.3	1,210	247.8	1,710	175.3	2,210	135.7
220	1,363	720	416.4	1,220	245.8	1,720	174.3	2,220	135.1
230	1,304	730	410.7	1,230	243.8	1,730	173.3	2,230	134.4
240	1,249	740	405.2	1,240	241.8	1,740	172.3	2,240	133.8
250	1,199	750	399.8	1,250	239.9	1,750	171.3	2,250	133.3
260	1,153	760	394.5	1,260	238.0	1,760	170.4	2,260	132.7
270	1,110	770	389.4	1,270	236.1	1,770	169.4	2,270	132.1
280	1,071	780	384.4	1,280	234.2	1,780	168.4	2,280	131.5
290	1,034	790	379.5	1,290	232.4	1,790	167.5	2,290	130.9
300	999.4	800	374.8	1,300	230.6	1,800	166.6	2,300	130.4
310	967.2	810	370.2	1,310	228.9	1,810	165.6	2,310	129.8
320	967.9	820	365.6	1,320	227.1	1,820	164.7	2,320	129.2
330	908.6	830	361.2	1,330	225.4	1,830	163.8	2,330	128.7
340	881.8	840	356.9	1,340	223.7	1,840	162.9	2,340	128.1
350	856.6	850	352.7	1,350	222.1	1,850	162.1	2,350	127.6
360	832.8	860	348.6	1,360	220.4	1,860	161.2	2,360	127.0
370	810.3	870	344.6	1.370	218.8	1,870	160.3	2,370	126.5
380	789.0	880	340.7	1.380	217.3	1,880	159.5	2,380	126.0
390	768.8	890	336.9	1.390	215.7	1,890	158.6	2,390	125.4
400	749.6	900	333.1	1,400	214.2	1,900	157.8	2,400	124.9
410	731.3	910	329.5	1,410	212.6	1,910	157.0	2,410	124.4
420	713.9	920	325.9	1,420	211.1	1,920	156.2	2,420	123.9
430	697.3	930	322.4	1,430	209.7	1,930	155.3	2,430	123.4
440	681.4	940	319.0	1,440	208.2	1,940	154.5	2,440	122.9
450	666.3	950	315.6	1,450	206.8	1,950	153.8	2,450	122.4
460	651.8	960	312.3	1,460	205.4	1,960	153.0	2,460	121.9
470	637.9	970	309.1	1,470	204.0	1,970	152.2	2,470	121.4
480	624.6	980	303.9	1,480	202.6	1,980	151.4	2,480	120.9
490	611.9	990	302.8	1,490	201.2	1,990	150.7	2,490	120.4
500	599.6	1,000	299.8	1,500	199.9	2,000	149.9	2,500	119.9

KILOCYCLES (kc) TO METERS (m), OR METERS TO KILOCYCLES
(Cont'd) [Columns Are Interchangeable]

kc or m	m or kc	kc or m	m or kc	kc or m	m or kc	kc or m	m or kc	kc or m	m or kc
2,510	119.5	3,010	99.61	3,510	85.42	4,010	74.77	4,510	66.48
2,520	119.0	3,020	99.28	3,520	85.18	4,020	74.58	4,520	66.33
2,530	118.5	3,030	98.95	3,530	84.94	4,030	74.40	4,530	66.19
2,540	118.0	3,040	98.62	3,540	84.70	4,040	74.21	4,540	66.04
2,550	117.6	3,050	98.30	3,550	84.46	4,050	74.03	4,550	65.89
2,560	117.1	3,060	97.98	3,560	84.22	4,060	73.85	4,560	65.75
2,570	116.7	3,070	97.66	3,570	83.98	4,070	73.67	4,570	65.61
2,580	116.2	3,080	97.34	3,580	83.75	4,080	73.49	4,580	65.46
2,590	115.8	3,090	97.03	3,590	83.52	4,090	73.31	4,590	65.32
2,600	115.3	3,100	96.72	3,600	83.28	4,100	73.13	4,600	65.18
2,610	114.9	3,110	96.41	3,610	83.05	4,110	72.95	4,610	65.04
2,620	114.4	3,120	96.10	3,620	82.82	4,120	72.77	4,620	64.90
2,630	114.0	3,130	95.79	3,630	82.60	4,130	72.60	4,630	64.76
2,640	113.6	3,140	95.48	3,640	82.37	4,140	72.42	4,640	64.62
2,650	113.1	3,150	95.18	3,650	82.14	4,150	72.25	4,650	64.48
2,660	112.7	3,160	94.88	3,660	81.92	4,160	72.07	4,660	64.34
2,670	112.3	3,170	94.58	3,670	81.70	4,170	71.90	4,670	64.20
2,680	111.9	3,180	94.28	3,680	81.47	4,180	71.73	4,680	64.06
2,690	111.5	3,190	93.99	3,690	81.25	4,190	71.56	4,690	63.93
2,700	111.0	3,200	93.69	3,700	81.03	4,200	71.30	4,700	63.79
2,710	110.6	3,210	93.40	3,710	80.81	4,210	71.22	4,710	63.66
2,720	110.2	3,220	93.11	3,720	80.60	4,220	71.05	4,720	63.52
2,730	109.8	3,230	92.82	3,730	80.38	4,230	70.88	4,730	63.39
2,740	109.4	3,240	92.54	3,740	80.17	4,240	70.71	4,740	63.25
2,750	109.0	3,250	92.25	3,750	79.95	4,250	70.55	4,750	63.12
2,760	108.6	3,260	91.97	3,760	79.74	4,260	70.38	4,760	62.99
2,770	108.2	3,270	91.69	3,770	79.53	4,270	70.22	4,770	62.86
2,780	107.8	3,280	91.41	3,780	79.32	4,280	70.05	4,780	62.72
2,790	107.5	3,290	91.13	3,790	79.11	4,290	69.89	4,790	62.59
2,800	107.1	3,300	90.86	3,800	78.90	4,300	69.73	4,800	62.46
2,810	106.7	3,310	90.58	3,810	78.69	4,310	69.56	4,810	62.33
2,820	106.3	3,320	90.31	3,820	78.49	4,320	69.40	4,820	62.20
2,830	105.9	3,330	90.04	3.830	78.28	4,330	69.24	4,830	62.07
2,840	105.6	3,340	89.77	3,840	78.08	4,340	69.08	4,840	61.95
2,850	105.2	3,350	89.50	3,850	77.88	4,350	68.92	4,850	61.82
2,860	104.8	3,360	89.23	3,860	77.67	4,360	68.77	4,860	61.69
2,870	104.5	3,370	88.97	3,870	77.47	4,370	68.61	4,870	61.56
2,880	104.1	3,380	88.70	3,880	77.27	4,380	68.45	4,880	61.44
2,890	103.7	3,390	88.44	3,890	77.07	4,390	68.30	4,890	61.31
2,900	103.4	3,400	88.18	3,900	76.88	4,400	68.14	4,900	61.19
2,910	103.0	3,410	87.92	3,910	76.68	4,410	67.99	4,910	61.06
2,920	102.7	3,420	87.67	3,920	76.48	4,420	67.83	4,920	60.94
2,930	102.3	3,430	87.41	3,930	76.29	4,430	67.68	4,930	60.82
2,940	102.0	3,440	87.16	3,940	76.10	4,440	67.53	4,940	60.69
2,950	101.6	3,450	86.90	3,950	75.90	4,450	67.38	4,950	60.57
2,960	101.3	3,460	96.65	3,960	75.51	4,460	67.22	4,960	60.45
2,970	100.9	3,470	86.40	3,970	75.52	4,470	67.07	4,970	60.33
2,980	100.6	3.480	86.16	3,980	75.33	4,480	66.92	4,980	60.20
2,990	100.3	3,490	85.91	3,990	75.14	4,490	66.78	4,990	60.08
3,000	99.94	3,500	85.66	4,000	74.96	4,500	66.63	5,000	59.96

KILOCYCLES (kc) TO METERS (m), OR METERS TO KILOCYCLES
(Cont'd) [Columns Are Interchangeable]

kc or m	m or kc	kc or m	m or kc	kc or m	m or kc	kc or m	m or kc	kc or m	m or kc
5,010	59.84	5,510	54.41	6,010	49.89	6,510	46.06	7,010	42.77
5,020	59.73	5,520	54.32	6,020	49.80	6,520	45.98	7,020	42.71
5,030	59.61	5,530	54.22	6,030	49.72	6,530	45.91	7,030	42.65
5,040	59.49	5,540	54.12	6,040	49.64	6,540	45.84	7,040	42.59
5,050	59.37	5,550	54.02	6,050	49.56	6,550	45.77	7,050	42.53
5,060	59.25	5,560	53.92	6,060	49.48	6,560	45.70	7,060	42.47
5,070	59.13	5,570	53.83	6,070	49.39	6,570	45.63	7,070	42.41
5,080	59.02	5,580	53.73	6,080	49.31	6,580	45.57	7,080	42.35
5,090	58.90	5,590	53.64	6,090	49.23	6,590	45.50	7,090	42.29
5,100	58.79	5,600	53.54	6,100	49.15	6,600	45.43	7,100	42.23
5,110	58.67	5,610	53.44	6,110	49.07	6,610	45.36	7,110	42.17
5,120	58.56	5,620	53.35	6,120	48.99	6,620	45.29	7,120	42.11
5,130	58.44	5,630	53.25	6,130	48.91	6,630	45.22	7,130	42.05
5,140	58.33	5,640	53.16	6,140	48.83	6,640	45.15	7,140	41.99
5,150	58.22	5,650	53.07	6,150	48.75	6,650	45.09	7,150	41.93
5,160	58.10	5,660	52.97	6,160	48.67	6,660	45.02	7,160	41.87
5,170	57.99	5,670	52.88	6,170	48.59	6,670	44.95	7,170	41.82
5,180	57.88	5,680	52.79	6,180	48.51	6,680	44.88	7,180	41.76
5,190	57.77	5,690	52.69	6,190	48.44	6,690	44.82	7,190	41.70
5,200	57.66	5,700	52.60	6,200	48.36	6,700	44.75	7,200	41.64
5,210	57.55	5,710	52.51	6,210	48.28	6,710	44.68	7,210	41.58
5,220	57.44	5,720	52.42	6,220	48.20	6,720	44.62	7,220	41.53
5,230	57.33	5,730	52.32	6,230	48.13	6,730	44.55	7,230	41.47
5,240	57.22	5,740	52.23	6,240	48.05	6,740	44.48	7,240	41.41
5,250	57.11	5,750	52.14	6,250	47.97	6,750	44.42	7,250	41.35
5,260	57.00	5,760	52.05	6,260	47.89	6,760	44.35	7,260	41.30
5,270	56.89	5,770	51.96	6,270	47.82	6,770	44.29	7,270	41.24
5,280	56.78	5,780	51.87	6,280	47.74	6,780	44.22	7,280	41.18
5,290	56.68	5,790	51.78	6,290	47.67	6,790	44.16	7,290	41.13
5,300	56.57	5,800	51.69	6,300	47.59	6,800	44.09	7,300	41.07
5,310	56.46	5,810	51.60	6,310	47.52	6,810	44.03	7,310	41.02
5,320	56.36	5,820	51.52	6,320	47.44	6,820	43.96	7,320	40.96
5,330	56.25	5,830	51.43	6,330	47.36	6,830	43.90	7,330	40.90
5,340	56.15	5,840	51.34	6,340	47.29	6,840	43.83	7,340	40.85
5,350	56.04	5,850	51.25	6,350	47.22	6,850	43.77	7,350	40.79
5,360	55.94	5,860	51.16	6,360	47.14	6,860	43.71	7,360	40.74
5,370	55.83	5,870	51.08	6,370	47.07	6,870	43.64	7,370	40.68
5,380	55.73	5,880	50.99	6,380	46.99	6,880	43.58	7,380	40.63
5,390	55.63	5,890	50.90	6,390	46.92	6,890	43.52	7,390	40.57
5,400	55.52	5,900	50.82	6,400	46.85	6,900	43.45	7,400	40.52
5,410	55.42	5,910	50.73	6,410	46.77	6,910	43.39	7,410	40.46
5,420	55.32	5,920	50.65	6,420	46.70	6,920	43.33	7,420	40.41
5,430	55.22	5,930	50.56	6,430	46.63	6,930	43.26	7,430	40.35
5,440	55.11	5,940	50.47	6,440	46.56	6,940	43.20	7,440	40.30
5,450	55.01	5,950	50.39	6,450	46.48	6,950	43.14	7,450	40.24
5,460	54.91	5,960	50.31	6,460	46.41	6,960	43.08	7,460	40.19
5,470	54.81	5,970	50.22	6,470	46.34	6,970	43.02	7,470	40.14
5,480	54.71	5,980	50.14	6,480	46.27	6,980	42.95	7,480	40.08
5,490	54.61	5,990	50.05	6,490	46.20	6,990	42.89	7,490	40.03
5,500	54.51	6,000	49.97	6,500	46.13	7,000	42.83	7,500	39.98

Kilocycles (kc) to Meters (m), or Meters to Kilocycles

(Cont'd) [Columns Are Interchangeable]

kc or m	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*	*kc or m*	*m or kc*
7,510	39.92	8,010	37.43	8,510	35.23	9,010	33.28	9,510	31.53
7,520	39.87	8,020	37.38	8,520	35.19	9,020	33.24	9,520	31.49
7,530	39.82	8,030	37.34	8,530	35.15	9,030	33.20	9,530	31.46
7,540	39.76	8,040	37.29	8,540	35.11	9,040	33.17	9,540	31.43
7,550	39.71	8,050	37.24	8,550	35.07	9,050	33.13	9,550	31.39
7,560	39.66	8,060	37.20	8,560	35.03	9,060	33.09	9,560	31.36
7,570	39.61	8,070	37.15	8,570	34.98	9,070	33.06	9,570	31.33
7,580	39.55	8,080	37.11	8,580	34.94	9,080	33.02	9,580	31.30
7,590	39.50	8,090	37.06	8,590	34.90	9,090	32.98	9,590	31.26
7,600	39.45	8,100	37.01	8,600	34.86	9,100	32.95	9,600	31.23
7,610	39.40	8,110	36.97	8,610	34.82	9,110	32.91	9,610	31.20
7,620	39.35	8,120	36.92	8,620	34.78	9,120	32.88	9,620	31.17
7,630	39.29	8,130	36.88	8,630	34.74	9,130	32.84	9,630	31.13
7,640	39.24	8,140	36.83	8,640	34.70	9,140	32.80	9,640	31.10
7,650	39.19	8,150	36.79	8,650	34.66	9,150	32.77	9,650	31.07
7,660	39.14	8,160	36.74	8,660	34.62	9,160	32.73	9,660	31.04
7,670	39.09	8,170	36.70	8,670	34.58	9,170	32.70	9,670	31.01
7,680	39.04	8,180	36.65	8,680	34.54	9,180	32.66	9,680	30.97
7,690	38.99	8,190	36.61	8,690	34.50	9,190	32.62	9,690	30.94
7,700	38.04	8,200	36.56	8,700	34.46	9,200	32.59	9,700	30.91
7,710	38.89	8,210	36.52	8,710	34.42	9,210	32.55	9,710	30.88
7,720	38.84	8,220	36.47	8,720	34.38	9,220	32.52	9,720	30.85
7,730	38.79	8,230	36.43	8,730	34.34	9,230	32.48	9,730	30.81
7,740	38.74	8,240	36.39	8,740	34.30	9,240	32.45	9,740	30.78
7,750	38.69	8,250	36.34	8,750	34.27	9,250	32.41	9,750	30.75
7,760	38.64	8,260	36.30	8,760	34.23	9,260	32.38	9,760	30.72
7,770	38.59	8,270	36.25	8,770	34.19	9,270	32.34	9,770	30.69
7,780	38.54	8,280	36.21	8,780	34.15	9,280	32.31	9,780	30.66
7,790	38.49	8,290	36.17	8,790	34.11	9,290	32.27	9,790	30.63
7,800	38.44	8,300	36.12	8,800	34.07	9,300	32.24	9,800	30.59
7,810	38.39	8,310	36.08	8,810	34.03	9,310	32.20	9,810	30.56
7,820	38.34	8,320	36.04	8,820	33.99	9,320	32.17	9,820	30.53
7,830	38.29	8,330	35.99	8,830	33.95	9,330	32.14	9,830	30.50
7,840	38.24	8,340	35.95	8,840	33.92	9,340	32.10	9,840	30.47
7,850	38.19	8,350	35.91	8,850	33.88	9,350	32.07	9,850	30.44
7,860	38.14	8,360	35.86	8,860	33.84	9,360	32.03	9,860	30.41
7,870	38.10	8,370	35.82	8,870	33.80	9,370	32.00	9,870	30.38
7,880	38.05	8,380	35.78	8,880	33.76	9,380	31.96	9,880	30.35
7,890	38.00	8,390	35.74	8,890	33.73	9,390	31.93	9,890	30.32
7,900	37.95	8,400	35.69	8,900	33.69	9,400	31.90	9,900	30.28
7,910	37.90	8,410	35.65	8,910	33.65	9,410	31.86	9,910	30.25
7,920	37.86	8,420	35.61	8,920	33.61	9,420	31.83	9,920	30.22
7,930	37.81	8,430	35.57	8,930	33.57	9,430	31.79	9,930	30.19
7,940	37.76	8,440	35.52	8,940	33.54	9,440	31.76	9,940	30.16
7,950	37.71	8,450	35.48	8,950	33.50	9,450	31.73	9,950	30.13
7,960	37.67	8,460	35.44	8,960	33.46	9,460	31.69	9,960	30.10
7,970	37.62	8,470	35.40	8,970	33.42	9,470	31.66	9,970	30.07
7,980	37.57	8,480	35.36	8,980	33.39	9,480	31.63	9,980	30.04
7,990	37.52	8,490	35.31	8,990	33.35	9,490	31.59	9,990	30.01
8,000	37.48	8,500	35.27	9,000	33.31	9,500	31.56	10,000	29.98

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